

Wiring America: The Short- and Long-Run Effects of Electricity Grid Expansion*

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Abstract

The US needs significant investment in electricity transmission lines in order to decarbonize the power sector. This paper examines the short- and long-run effects of large scale electricity grid expansion. I focus on the rollout of a grid expansion project that linked windy areas in west Texas to population centers in the east. Short-run analysis shows that: (1) Transmission expansion led to moderate declines in fossil fuel generator markups, about 2.5% during peak demand hours and 7% during off-peak hours. (2) It also prevented \$53 million (2020 \$) worth of annual damages from emissions. Long-run analysis finds evidence of higher wind capacity (+202%), more wind turbines (+245%), and bigger wind projects (+121%) in counties with transmission infrastructure. These results highlight that investments in grid level storage and upgrades can be useful in enhancing the value of estimated benefits.

Keywords: Electricity Markets, Emissions, Energy, Transmission Expansion, Wind

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1 Introduction

The US aims to achieve a carbon-free power sector by 2035 (The White House 2021). Most wind and solar generators in the US produce electricity in geographic locations far from where electricity is consumed. Transmission lines enable moving this electricity over long distances to the demand centers. Transitioning to an electricity grid that fully realizes the benefits from renewable energy will require substantial investment in transmission lines. This issue has been covered widely in both energy and popular news outlets, pointing out the imminent necessity to build transmission lines in order to dramatically cut carbon emissions and achieve ambitious energy goals (New York Times 2016; Temple 2017; Meyer 2021).

In this paper, I study how large scale transmission expansion projects aimed at integration of renewable energy affect firm entry, pricing behavior, and emissions. I first study the short-run impact of transmission expansion on fossil fuel generator markups, local and global emissions while keeping wind generation capacity fixed. I then study the long-run investment in wind energy in response to transmission expansion. To answer these questions, I focus on the rollout of a large scale transmission expansion project called Competitive Renewable Energy Zones (CREZ) in Texas. Costing about \$7 billion, the CREZ transmission expansion was aimed at integrating the wind resources in West Texas with the major demand centers in other parts of the state. The construction of this project started in 2011 with more than 80 percent of the rollout happening in 2013.

There are several interesting features of the Texas electricity market that make it an excellent context for this paper. First, the roll-out of CREZ over 2011 - 2013 provides an ideal setting to study effects of large scale transmission projects. Second, there has been a gradual increase in the generating capacity of wind over the years. In 2011, wind represented about 13 percent of the total electricity generating capacity which grew to over 25 percent by the end of 2020 (ERCOT 2012, 2021). Finally, the Texas electricity interconnection is isolated from other electricity markets in the US, which avoids spillover effects due to imports or exports of electricity from other markets.

For the short-run analysis, I build a model of optimal bidding for a fossil fuel generator to understand how transmission line expansion affects its incentives to set markups. I write this model in the context of a uniform auction wherein the generator participates

by bidding the price and quantity of electricity (as a function of price) that it is willing to supply in a particular period. The generator maximizes its profit over its residual demand curve to find the optimal price of electricity to supply. I specifically focus on the case of the marginal generator since its optimal bid determines the wholesale price. Therefore, the markups set by the marginal generator(s) is the realized markup prevailing in the market. Solving the generator's optimization problem allows me to derive the optimal markup rule as a function of its residual demand curve.

The model yields several predictions on how large scale transmission expansion affects the marginal generator's markups. More generally, the ability of a generator to set markups depends on two factors. First, the extent to which wind generation displaces production from competing fossil fuel generators. Second, the degree to which market integration and wind generation affects the competition amongst generators with heterogeneous costs of producing electricity. The relative magnitudes and directions of these two effects determine whether the generator sets higher or lower markups.

Based on the theoretical model, I construct a two-step estimator to examine how transmission expansion affects markups. I use hourly generator level data on markups from 2011 to 2014 and a fixed effects model for this analysis. In the first step, I estimate the effect of transmission expansion on hourly wind generation, followed by estimating the effect of wind generation on hourly markups set by marginal generator(s). I find that CREZ expansion led to an average decline in markups by about 2.5 percent during the peak demand hours and about 7 percent during the off peak hours. Therefore, the potential of transmission capacity to affect markups depends on how much wind generation is integrated into the grid.

The short-run analysis on the emissions finds a decline in emissions to the order of \$53 million (2020 \$) annually due to CREZ expansion. About 60 percent of the damages avoided are from local pollutants (SO_2 and NO_x) with the remaining share from carbon emissions. I find evidence of spatial heterogeneity in the damages avoided due to carbon emissions, however, the decline in local pollutants comes mainly from the West of Texas. The estimates show an increase in emissions due to ramping up of coal generators at the margin as a result of wind intermittency during the early hours of the day. Thus, availability of excess transmission capacity near the marginal coal generators during the

periods of low wind could exacerbate the damages from emissions in populated locations.

Next, I analyze whether locations that receive investment in transmission infrastructure also see higher levels of wind investment in the long-run. I implement an instrumental variable and a matching strategy to answer this question. I use the designation of certain regions in Texas into five Renewable Energy (RE) Zones by the Public Utilities Commission of Texas in 2007 as an instrument for a county to receive CREZ transmission infrastructure (i.e. CREZ county). The goal of identifying RE Zones was to narrow the set of suitable locations for transmission expansion so as to support the existing and growing wind capacity in West Texas. Conditional on wind resource quality, county demographics, and wind regulation; RE Zones is unlikely to affect long-run wind investment other than by inducing the selection of counties as CREZ. IV estimates suggest that CREZ expansion on an average led to about 62 MW (+189%) higher wind capacity and 30 more turbines (+191%) in treated counties over 2012 - 2019.

I use a matching strategy to alleviate the concerns of the common support problem in comparing treated counties that are inherently different than control counties in the IV regressions. I use Coarsened Exact Matching to construct a set of control counties that are identical to the treated counties on a wide set of observable dimensions. The treatment effect for the matched sample suggests 73 MW (+202%) higher wind capacity, 40 more turbines (+245%), and about 33 MW (+121%) bigger wind projects in treated counties. Taken together, these results provide robust causal evidence that transmission expansion spurs investment in wind generation in the long-run. A back of the envelope calculation shows that the wind capacity added due to CREZ expansion could power about 2.6 percent Texas households during the periods of peak electricity demand in 2019. This is economically significant since the total wind capacity in Texas in 2019 could power about 21 percent of total households at peak demand.

Related Literature. This study builds on the insights from several sets of papers. First, it adds to the extensive literature on the incidence and consequences of market power in wholesale electricity markets. Studies focused on electricity markets post deregulation have found market power contributing to high wholesale electricity prices (Borenstein, Bushnell, and Wolak 2002) and misallocation due to sub-optimal bidding

behavior (Hortacsu and Puller 2008; Hernández 2018). Existence of market power in sequential electricity markets is found to result in price premium across markets by causing lack of arbitrage (Saravia 2003; Borenstein et al. 2008; Ito and Reguant 2016). Several studies have highlighted the role of financial arbitrage (Borenstein et al. 2008; Birge et al. 2018; Mercadal 2018), vertical structures, and forward contracting in mitigating market power (Bushnell, Mansur, and Saravia 2008).

Second, I contribute to the growing literature focusing on the value of transmission infrastructure in mitigating market power in wholesale electricity markets. Theoretical studies in this area employ Cournot models and simulations to show how expansion in transmission capacity leads to higher competition and mitigates the effects of market power (Borenstein, Bushnell, and Stoft 2000; Joskow and Tirole 2000, 2005). Recent empirical literature has looked at the welfare effects of geographical integration in electricity markets (Davis and Hausman 2016) and the effects of transmission constraints in exacerbating the market power exercised by generating firms (Woerman 2019; Ryan 2021).

My theoretical model is most closely related to Ryan (2021) who derives the optimal bidding condition for a fossil fuel generator and uses structural estimation to simulate the effects of transmission expansion in the Indian electricity market. I add to this model by deriving conditions under which integration of renewable energy due to transmission expansion could incentivize fossil fuel generators to set lower markups. The theoretical model in this paper is tailored to the empirical context that I analyze. A potential contribution of this model is that its findings are applicable to similar transmission expansion projects in the US. This is relevant for electricity markets in the Midwest where renewable generators located in remote regions and high voltage transmission lines are needed to deliver power to demand centers.

Third, this paper contributes to the nascent literature looking at the link between transmission expansion, wind energy, and the wholesale electricity prices. This builds upon the empirical literature in economics exploring the impact of renewable generation in lowering emissions in the power sector (Cullen 2013; Kaffine, McBee, and Lieskovsky 2013; Novan 2015; Fell and Kaffine 2018; Fell and Johnson 2021). Recent papers study how CREZ expansion in Texas enhanced the environmental value of wind measured by

emissions avoided (Fell, Kaffine, and Novan 2021) and had significant impacts on lowering market prices (LaRiviere and Lu 2020; Doshi and Du 2021). I complement this literature in two ways. First, I show how intermittency of wind could lead to higher emissions from marginal generator(s). This could eat away some of the estimated short-run gains due to transmission expansion. Second, utilizing the spatial data on CREZ expansion, I provide first causal evidence in the literature on the long term investment in wind energy in response to transmission expansion.

Finally, the findings in this paper have several policy implications. The short-run impacts on markups and emissions highlight the role of grid-scale energy storage. This technology can be instrumental in not only reducing wind curtailment during periods of high wind but also reducing fossil fuel markups at peak hours when wind generation is low. It could also mitigate the rise in emissions due to intermittency of wind during early hours of the day. The results in this paper speak to the potential impacts of large scale grid expansion projects in other parts of the US. For instance, grid expansion can be instrumental in addressing the dropping out of thousands of megawatts of renewable energy projects from development due to inadequate transmission capacity in the Mid-continent ISO (Thill 2020). These results also underscore the necessity of investments in grid upgrades and resiliency so that additional wind does not strain the grid during periods of congestion and temperature shocks.

Outline. The remainder of this paper is organized as follows. Section 2 describes the institutional context along with the CREZ expansion project. I provide a description of the data and the variables along with descriptive statistics in Section 3. The theoretical model for the short-run, empirical strategy, and results are presented in Section 4. The long-run analysis of CREZ expansion and wind project investment is presented in Section 6. Section 7 provides a concluding discussion and policy implications of the results.

2 Institutional Details

2.1 The Texas electricity market

The Texas electricity market is one of the major deregulated electricity markets in the US. Electric Reliability Council of Texas (ERCOT) is mandated to maintain system reliability and manage the wholesale and retail electricity markets in Texas. One of the major tasks of ERCOT is scheduling supply from generators in order to meet demand for electricity at all times. It does so by organizing a series of sequential auctions and real-time market operations. In this paper, I focus solely on the real time-market decisions by fossil fuel generators.

Even though the ERCOT interconnection spans a single state geographically, it overlooks over 46,500 miles of electricity transmission and 700 generators serving electricity demand from over 26 million consumers. As of 2020, Natural Gas represented about 51 percent of electricity generating capacity followed by 25 percent by wind and 13.4 percent by Coal (ERCOT 2021). In terms of emissions, in 2019 power sector contributed to about 212.4 million metric tonnes of CO₂ emissions in 2017, about 12.3 percent of the total CO₂ emissions from the power sector in the US (EIA 2019). Clearly, Texas is an important context to study the behavior of fossil fuel generators and their environmental impact.

The ERCOT interconnection is comprised of six zones within Texas - Panhandle, West, North, South, Houston, and Coastal. Figure 1 provides a sense of geographic distribution of counties in these zones. Wind rich Panhandle and West Zone is where most of the wind generation of Texas comes from. North and the South Zones host most of the fossil fuel generating firms along with major demand centers like Dallas-Fort Worth Area, San Antonio, and Austin. Houston forms the fourth zone which is a major demand center in itself. These zones are connected by a network of over 46,500 miles of transmission lines that carried about 74,820 MW of electricity at a record peak demand on August 12, 2019 (ERCOT 2021).¹

1. To put this in perspective, this amount of electricity is equivalent to powering about 15 million Texas homes during periods of peak demand (ERCOT 2021).

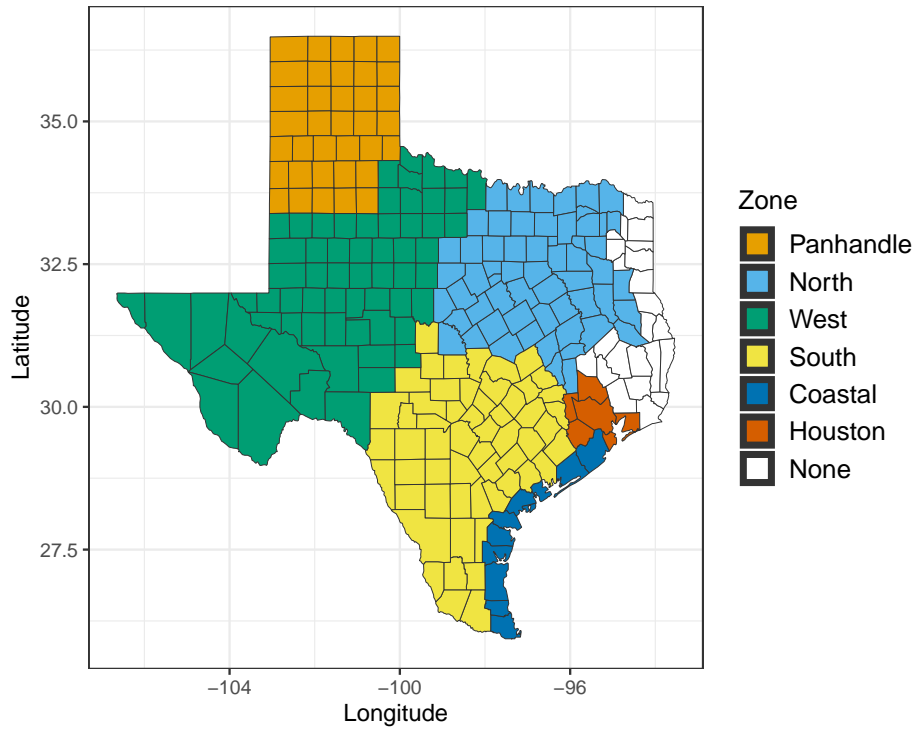


Figure 1: ERCOT Zones Map

2.2 Competitive Renewable Energy Zones

An interesting aspect of the Texas electricity market is the increasing capacity of wind based power generation. Since ERCOT schedules lowest cost generation to dispatch first, wind based generators are always scheduled to dispatch first. Thus conditional on wind flow, wind based generating units are always scheduled to meet the demand. Fossil fuel generators on the other hand are dispatched to meet the remaining demand as well as to meet any sudden surge in demand at Peak hours.²

Inadequate transmission capacity between West and other Zones in Texas could lead to transmission congestion in a way that prevents trade of electricity from West to demand centers in other parts of the state. Recall that most of the wind based electricity generation in Texas comes from the West. The presence of transmission constraints could

2. ERCOT defines Peak hours as hours ending in 07:00 to 22:00 from Monday through Friday. The remaining hours are classified as Off-Peak hours. Wind based generators and low marginal cost fossil fuel generators are usually the base-load units whereas Natural Gas units are typically used to meet peak demand because of their ability to ramp-up at low cost at short notice.

cause ERCOT to schedule electricity from local generating units that are typically fossil fuel fired generators. This not only leads to CO₂ emissions that could've been offset by clean wind based electricity but also incentivize local fossil fuel generators to charge a markup over their marginal cost of production.

I examine this phenomenon under the backdrop of a recent transmission expansion project in Texas, Competitive Renewable Energy Zones (CREZ). CREZ was a large scale transmission expansion project aimed at integrating electricity generation from wind farms located in West to the major demand centers in North, South, and Houston Zones. The project, commissioned in 2008 by the Public Utilities Commission of Texas was aimed to accommodate over 18.5 GW of electric power by building about 3,600 circuit miles of 345 kV electricity transmission lines. However, the transmission lines are open access meaning that the use is not limited to only wind generators (Billo 2017). Transmission lines were built over a period of 2011 through 2013 with a total cost of approximately \$6.8 billion. All of the CREZ based transmission lines were brought in service by December 2013. The CREZ expansion project has been credited in reducing transmission congestion and wind curtailment in Texas (Lasher 2014).

3 Data and Variables

I assemble multiple datasets with varying temporal resolution. For the short-run analysis of generator markups, I assemble a hourly generator level dataset from 2011 through 2014. For the long-run analysis on wind investment, I construct an annual dataset of wind and fossil fuel generators from 2001 through 2019. Most of my data comes from publicly available sources like ERCOT, the Energy Information Administration (EIA), and the Environmental Protection Agency (EPA).

3.1 Electricity Generation and Demand

I use hourly electricity generation data at the generator level for fossil fuel generators and data on system wide electricity generation from wind from ERCOT. The electricity generation data is used to construct marginal costs and data on wind generation is a variable of interest in the empirical specifications. I also use hourly data on system electricity demand from ERCOT.

3.2 Markups

One of the main outcomes of interest for the short-run analysis is the generator markups. Markups are defined as $p - c$ where p is the Locational Marginal Price (LMP) and c is the marginal cost. I use publicly data available from ERCOT to identify the price setting (marginal) generators and the corresponding LMP at each hour of the sample. The other component of markup is the marginal cost of generation. The generating technology assumes constant marginal cost of generation since fuel costs remains constant. The assumption of constant marginal costs is also common in the literature. The two major components of marginal cost are fuel costs and emissions permit costs based on emissions regulations for SO₂ and NO_x. I calculate the marginal cost of each generator as the sum of these two components.

To compute fuel costs, I use weekly price data for coal and natural gas. For coal, I use Powder River Basin spot prices from EIA. For natural gas, I use Henry Hub Natural Gas prices from Quandl. I calculate fuel costs by multiplying fuel price and the heat rate (HR_{*i*}) of the generator.³ To compute the emissions permit costs, I use daily data on NO_x and SO₂ allowances from S&P Global Market Intelligence. Using hourly emissions data from EPA's Continuous Emissions Monitoring system (CEMS), I calculate the emissions rate (ER_{*i*}) for SO₂ and NO_x by taking the ratio of emissions to net generation.⁴ The generator's emission permit cost is thus the product of the permit price and emissions rate for each emission type. Thus, the marginal cost c_{it} of generator i in period t is:

$$c_{it} = \text{HR}_{it} \cdot p_t^{\text{fuel}} + \text{ER}_{it}^{\text{SO}_2} \cdot p_t^{\text{SO}_2} + \text{ER}_{it}^{\text{NO}_x} \cdot p_t^{\text{NO}_x} \quad (1)$$

Figure 2 shows the distribution of marginal costs (\$/MWh) of coal and natural gas generators in the sample. The dashed lines in Figure 2 mark the average for both fuel types. The distribution of marginal cost for both the fuels is a right skewed distribution with the averages below \$25/MWh for both the fuel types. The average marginal cost for coal generators is slightly higher than that of natural gas generators.

3. EIA defines heat rate as the amount of energy used by a power plant to produce 1 KiloWatt-hour (kWh) of electricity. It is calculated as a ratio of fuel input to net electricity generated and is expressed in British thermal units (Btu) per net kWh.

4. Due to Clean Air Act (CAA) electricity generators are subjected to emissions regulations for SO₂, NO_x or both. Generators are required to purchase emission permits for each ton of emissions (SO₂ and NO_x) they emit.

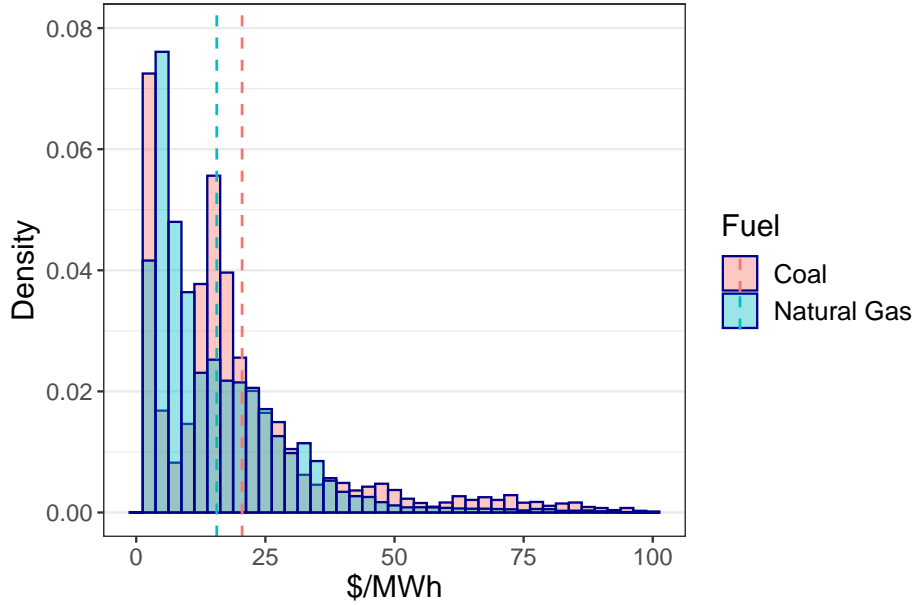


Figure 2: Distribution of marginal costs (\$/MWh) of coal and natural gas generators

Note: Vertical lines denote the mean marginal costs.

Table 1 reports descriptive statistics of generator markups and nameplate capacity by fuel types of generators in the sample. About 70 percent of the observations in the sample are natural gas fired generators whereas coal generators are the remaining 30 percent. From Panel A. in Table 1, the average realized markups set by natural gas generators is about \$17.16/MWh which is about three times the average markups of coal generators. This follows from the overall generation pattern in the Texas electricity market wherein coal generators tend to be marginal during the night and early hours of the day whereas natural gas generators operate at the margin during the peak demand hours. From Panel C. the coal generators have an average nameplate capacity of 603 MW whereas natural gas generators are 192 MW.

Generator markups exhibit quite a lot of hourly variation which is not apparent from Table 1. Further, the level of hourly variation also changes over time. To show these patterns I plot the average hourly markups of marginal generators from 2011 to 2014 in Figure 3b. From Figure 3b, we see that on an average markups were about \$50/MWh during the peak hour of 16:00 in 2011 and 2013. However, we can see a dramatic drop in

Table 1: Descriptive statistics of generator markups and nameplate capacity by fuel type

| A. Realized Markups (\$/MWh) | | | | | | |
|------------------------------|--------|--------|--------|--------|---------|----------|
| Fuel | Mean | Median | SD | Min | Max | Freq.(%) |
| Coal | 5.73 | 7.26 | 30.77 | -98.78 | 4597.90 | 31.87 |
| Natural Gas | 17.16 | 15.17 | 60.42 | -87.32 | 4899.21 | 68.13 |
| B. Nameplate Capacity (MW) | | | | | | |
| Fuel | Mean | Median | SD | Min | Max | Freq.(%) |
| Coal | 603.18 | 615 | 199.73 | 174.6 | 1008 | 31.87 |
| Natural Gas | 191.86 | 178.2 | 89.78 | 25 | 765 | 68.13 |

Note: This table presents descriptive statistics for the observations for the markup analysis. Each observation corresponds to the marginal generator(s) at a particular hour. Freq.(%) in each panel refers to the frequency (in percentage) a marginal generator is of specific fuel type in the sample.

markups in 2014 across all peak hours (13:00 - 17:00), perhaps most significant at 16:00 . Average markups are similar over the years for off-peaks hours (0:00 - 12:00 and 18:00 - 23:00), suggesting that CREZ expansion had the strongest effect for peak demand hours.

3.3 CREZ Transmission Expansion

Another key variable in the analysis of generator markups is the progress of CREZ transmission expansion. I use the publicly available Transmission Project and Information Tracking reports from ERCOT's website to construct a variable that tracks total miles of transmission lines built in a day under the CREZ expansion project. I express the CREZ progress variable as a cumulative ratio for ease of interpretation. As shown in Figure 3a even though the CREZ project was started in 2010, over 80 percent of the project was completed in 2013.

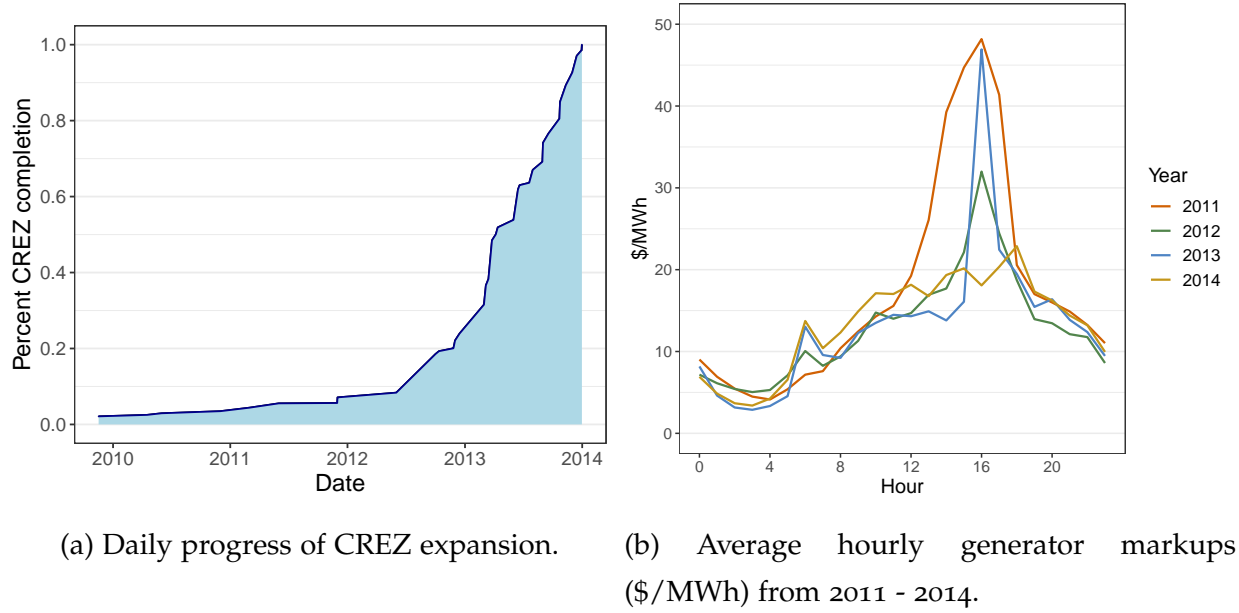


Figure 3: Daily CREZ progress and generator markups over the years

4 Short-run: Impact of CREZ Expansion on Markups

4.1 Real-time electricity market

For this analysis, I focus on the real-time electricity market which sets the expectation for prices in the day-ahead and forward markets (Potomac Economics 2019). The main purpose of a real-time market is to match supply with demand while operating the transmission system within established limits. Real-time operations involve participation from various market participants like generators, retailers, transmission service providers, and distributors. ERCOT serves as the regulatory body that manages the efficient operation of the real-time market.

Real-time market operations mainly refers to the operating hour and the hour immediately preceding the operating hour. ERCOT collects the status of all the transmission infrastructure from Transmission Service Providers and identifies transmission constraints and forecasts demand at various points of the network for the operating hour. This information is made available to the supply side of the market that comprises of the generating firms.

To participate in the market, each firm submits offer curves for all the generators that it owns. These offer curves are monotonically increasing vectors of price-quantity pairs based on the demand and grid information provided by ERCOT. Firms enjoy great flexibility to specify and alter their offer curves which can be different for different hours of the day. They can input up to ten price-quantity pairs and alter their offer curve up to the hour preceding the operating hour. As noted in (Woerman 2019), this allows a firm to update its strategy when more information on various factors like demand, transmission constraints, or strategies of competitors is available.

The demand side of the market is comprised of retailers and load serving entities who submit demand for energy at various locations in the operating hour. Equipped with the information on supply, demand, and transmission constraints, ERCOT deploys a market clearing process that occurs every 5 minutes. This process identifies least cost generating resources that would meet the electricity demand at various locations in the system while respecting transmission constraints and the capacity limits of the generating resources. Apart from matching supply to demand, a major task of this process is to prevent the system from exceeding operational limits thus maintaining the reliability of the network. This market clearing process generates market clearing prices called Locational Marginal Price which is the location specific wholesale price of electricity.

4.2 Transmission Constraints and Market Power

Transmission constraints play a major role in determining the cost effective dispatch of generating resources. To understand how, it is important to recognize the role played by transmission infrastructure in electricity markets. Presence of transmission essentially enables flow of electricity between two points. Typically, generating units are located at regions far away from the demand centers. Therefore, a transmission network that is able to carry electricity from supply to demand at all times is of prime importance.

One of the main features of transmission lines is that they operate under certain capacity limits that need to be maintained. Transmission constraints between two points A and B are said to be binding when transmission lines between them operate at their maximum capacity. This is another way of saying that the transmission lines are congested. There could be various reasons for transmission congestion or binding transmis-

sion constraints, like increase in demand due to weather conditions, outages, insufficient transmission infrastructure to name a few.

Presence of transmission constraints prevents ERCOT from dispatching the cost effective generating units to meet the demand at a particular location. To see this, consider a simple example. Say there are two regions A and B. Region A consists of low cost generators that can provide up to 100 MW of electricity and region B consists of high cost generators that can also provide 100 MW of electricity. However, Region A and B are connected by a transmission line that can carry only 50 MW of electricity. Suppose at some time t there is a demand for 80 MW of electricity in region B by households. ERCOT as the planner, would like to dispatch all of the 80 MW from low cost generators in Region A. However, due to the transmission limit it can only dispatch 50 MW. At this point, the transmission constraint between A and B is said to be binding or there is transmission congestion between A and B. To meet the remaining demand, ERCOT has to dispatch 30 MW of electricity from high cost generators located in region B. Thus, presence of transmission constraints leads to dispatch of higher cost generators when the demand could have been met by low cost generators.⁵

A natural question is, how does presence of transmission constraints translate to generators firms exercising market power? Recall that generators submit monotonically increasing offer curves that determines the price of electricity they would charge for a certain quantity. A firm could anticipate demand and transmission constraints and hence submit a bid that is composed of the marginal cost of supplying electricity and a markup term.⁶ As I show in the theoretical model in Section 4, this markup term is dependent on the shape of the residual demand curve that the generator faces in the market which in turn is a function of transmission capacity.

5. The dispatch of electricity in reality is more complicated since the flow of current follows Kirchhoff's Laws. This example abstracts from such real life aspects in order to illustrate the impact of transmission constraints on generator dispatch.

6. In ERCOT, generators do have access to demand forecasts and the information on transmission infrastructure. They use this publicly available information and any private information about the market to determine their offer curves.

4.3 A Model of Optimal Fossil Fuel Markups

The theoretical model in this section aims to understand the effect of transmission expansion on the pricing decision of a profit-maximizing fossil fuel generator. I borrow elements of the merchant transmission investment model by Joskow and Tirole (2005), but extend it by including electricity generation from renewable sources. My model is based on Ryan (2021), however, I differ from it in two key ways. First, I introduce a wind generating sector which is isolated from the demand centers. Second, in my model transmission expansion affects fossil fuel generators mainly by integrating electricity from the wind generating sector. This mimics my empirical setting wherein CREZ expansion impacted fossil fuel generators by integrating electricity generated by wind farms from the West. In what follows, I present the optimal markup rule for a fossil fuel generator and provide intuition on how it is affected by the transmission expansion.

4.3.1 Model Setup

Consider two geographically distinct regions \mathcal{W} and \mathcal{S} . Region \mathcal{W} is a wind rich region comprising of wind farms to produce electricity. Region \mathcal{S} , on the other hand is comprised of several fossil fuel fired electricity generators that serve a large demand center. The presence of electricity transmission capacity (K) enables trade of electricity generated from wind in region \mathcal{W} to demand centers in region \mathcal{S} .

In this model, I focus on pricing decision of a fossil fuel generator i that maximizes its profits in region \mathcal{S} . Generator i submits an offer curve that is a vector of supply quantities Q_i at bid prices b_i while incurring cost $C_i(Q_i)$. The optimization problem of i entails finding the offer curve that maximizes its profit function $\pi_i(p) = p \cdot Q_i(p) - C_i(Q_i(p))$, where p is the market clearing price that resolves in \mathcal{S} .

However, the generator faces uncertainty over the offer schedules $\mathcal{S}_{-i} = (b_{-i}, Q_{-i})$ from other fossil fuel generators ($-i$) in \mathcal{S} . Further, the generator has to consider any forward positions it has. I denote the forward price and quantity of generator as p^F and Q_i^F respectively. Therefore, the optimization problem is,

$$\max_{b_i, Q_i} \mathbb{E}_{\mathcal{S}_{-i}} \left[p \cdot Q_i(p) - C_i(Q_i(p)) + (p^F - p)Q_i^F \right] \quad (2)$$

The last term in Equation 2 is the payoff from the forward position that is resolved in the real time market. Market demand in \mathcal{S} is denoted by D^S and is assumed to be perfectly inelastic. Generator i faces a downward sloping residual demand curve $D_i^r(p, q_w; K)$ which is comprised of three elements: Market demand D^S ; electricity generated from wind imported from \mathcal{W} , q_w ; and the total electricity generated from competitor fossil fuel generators, $Q_f(q_w, p) = \sum_{j \neq i, j \in \mathcal{S}} Q_j(q_w, p)$. I express Q_f as a function of q_w because the dispatch of a fossil fuel generator depends on the amount of electricity generated by wind.⁷ Recall that wind-based electricity generation incurs zero marginal cost and is always scheduled to dispatch first. $Q_f(q_w, p)$ is strictly increasing in p and strictly decreasing in q_w .⁸ Mathematically, D_i^r can be written as,

$$D_i^r(p, q_w; K) = D^S - q_w - Q_f(q_w, p) \quad (3)$$

The market clears when electricity generated by i equals residual demand, i.e. $Q_i(p) = D_i^r(p, q_w; K)$. The market clearing price p and the supply $Q_i(p, q_w)$ depend on the optimal bid price b_i that solves the generator i 's problem,

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

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,

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

Equation (4) is the optimal pricing rule for generator i wherein it sets price equal to marginal cost plus a markup term. $\frac{\partial p}{\partial b_i}$ is the slope of market clearing price in the bid price and is equal to one if the bid is marginal and zero otherwise. In this paper, I focus on the case when b_i is the marginal bid and therefore determines the market clearing

7. I assume $D^S > q_w$, otherwise there wouldn't be any need to schedule electricity from fossil fuel generators as all of the market demand could be met by wind.

8. The interpretation of these assumptions is as follows:

1. $\frac{\partial Q_f}{\partial p} = \sum_{j \neq i, j \in \mathcal{S}} \frac{\partial Q_j}{\partial p} > 0$: generators have greater incentives to supply electricity at higher prices.
2. $\frac{\partial Q_f}{\partial q_w} = \sum_{j \neq i, j \in \mathcal{S}} \frac{\partial Q_j}{\partial q_w} < 0$: electricity generated from wind displaces a non-zero amount of electricity from fossil fuel generators.

price. Thus, I refer to i as the marginal generator as its optimal bid sets the price. For simplicity, I assume constant marginal cost i.e. $C'_i(D'_i(p, K)) = c_i$ and full information on other generators' strategy. Equation (4) reduces to,

$$p - c_i = -\frac{Q_i^{net}(p, q_w)}{\partial D'_i(p, q_w) / \partial p} \quad (5)$$

Equation 5 shows that the markups are dependent on the net-production of electricity and the slope of its residual demand curve which is a negative quantity. The numerator measures the extent to which generator's production decision affects the markups. With $Q_i^{net} > 0$, the generator is a net seller implying that it withholds output in the forward market to raise the market clearing price in the real-time market such that $p - c_i > 0$. Similarly, with $Q_i^{net} < 0$, the generator is a net buyer and pays price less than the marginal cost for the electricity generated.

The denominator which is the slope of residual demand curve determines the ability of the generator to set markups. An flatter residual demand curve implies that the generator has a lower potential to set markups and thus submits more elastic offer curves. Similarly, a steeper residual demand curve implies that the generator has greater potential to set markups and therefore submits less elastic offer curves.

4.3.2 Predictions from the model

As shown in Equation (5), the extent of marginal generator i 's realized markup ($p - c_i$) depends on the shape of the residual demand curve. In order to characterize the effect of change in transmission lines on markups, I perform comparative statics exercise by partially differentiating Equation (5) with respect to K ,

$$\frac{\partial(p - c_i)}{\partial K} = \frac{\left[-\frac{\partial Q_i^{net}(p, q_w)}{\partial K} \cdot \frac{\partial D'_i(p, q_w)}{\partial p} \right] + \left[Q_i^{net}(p, q_w) \cdot \frac{\partial^2 D'_i(p, q_w)}{\partial p \partial K} \right]}{\left[\frac{\partial D'_i(p, q_w)}{\partial p} \right]^2} \quad (6)$$

I express Equation (6) as a percentage change in markups by multiplying both sides by the inverse of Equation (5). Algebraic simplification allows me to split the resulting expression into two terms that measure the effect of transmission line expansion on markups. I call these terms $\Delta Production$ and $\Delta Elasticity$ based on how they affect net production and elasticity of the residual demand curve.

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

$\Delta \text{Production}$. This term measures the percentage change in net-production by generator i in the real-time market due to change in transmission capacity K .

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

Proposition 1 *The addition of wind leads to an inward shift of marginal generator's residual demand curve.*

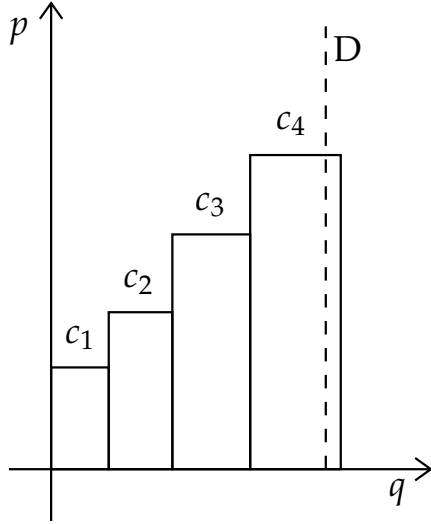
The first term in Equation (8) measures the extent to which production decision of generator i is affected by addition of wind energy. Consider a hypothetical electricity dispatch curve shown in Figure 4a. The supply side assumes four fossil fuel generators indexed by their offer/bid price $c_j (j = 4)$ of electricity they submit. The dispatch curve is a step function comprised of generators arranged in an increasing order of the offer price. The dotted vertical line (D) is the demand of electricity and is assumed to be fixed. Generators are dispatched in the increasing order of the offer price until the demand is met. The generator(s) with the highest offer price that is dispatched is the marginal generator and it determines the wholesale price of electricity.⁹ In the scenario below, generator i submits the highest offer price c_4 and is thus the marginal generator.

Consider the scenario in Figure 4b wherein wind (W) displaces electricity generated from i shown as the hashed area. Mathematically, this can be written as:

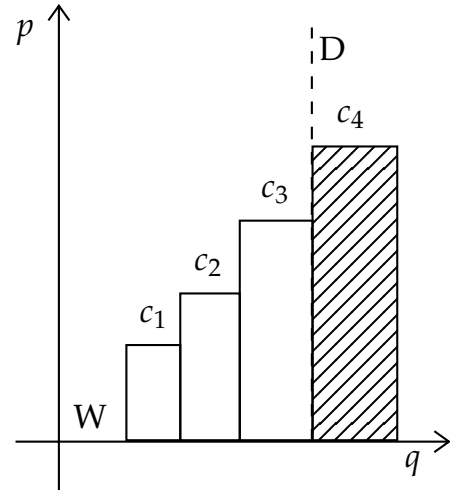
$$\frac{\partial Q^{net}}{\partial q_w} < 0 \quad (9)$$

Thus, electricity from wind shifts the dispatch curve to the right displaying electricity generated by the marginal generator i . This is reflected as an inward shift of i 's residual demand curve which in turn reduces i 's potential to set higher markups. This is shown in Figure 4c with the generator moving from point A to point B of its offer curve post wind integration. Compared to point A, point B is associated with the flatter region of the offer curve thereby reducing its ability to set higher markups.

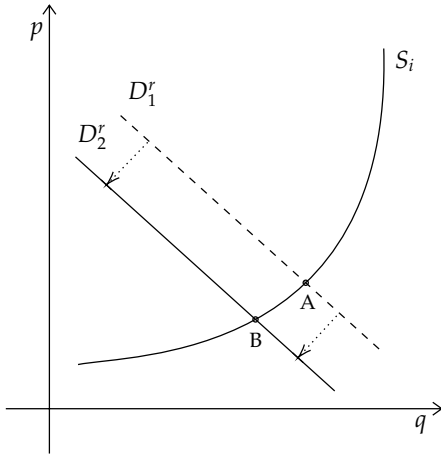
9. If there are multiple generators that have the highest offer price and are dispatched, all of them are referred to as marginal generators.



(a) Hypothetical dispatch curve



(b) Rightward shift in the dispatch curve due to additional wind generation (W).



(c) Shift in generator i 's residual demand curve (D_i^r) due to the addition of wind energy (W)

Figure 4: Hypothetical electricity dispatch curves and the effect of wind generation on marginal fossil fuel generator.

Note: c_i denotes the marginal cost of generator i . Vertical dotted line denotes the demand for electricity (D).

Proposition 2 *Transmission expansion leads to integration of electricity from wind into the grid.*

The second term in Equation (8) measures the change in import of electricity into \mathcal{S} from wind farms in \mathcal{W} due to a marginal increase in transmission capacity. Transmission expansion would enable higher imports of electricity generated from wind into \mathcal{S} , therefore $\partial q_w / \partial K \geq 0$.

Δ Elasticity. This term measures the marginal effect of transmission capacity on the slope of marginal generator i 's residual demand curve. To understand the direction of this term, I take the derivative of the slope of the generator i 's residual demand curve with respect to K . The slope of i 's residual demand curve depends only on the production decisions of its competitors as D^S and q_w are invariant to changes in p . Therefore,

$$\frac{\partial^2 D_i^r(p, q_w; K)}{\partial p \partial K} = - \frac{\partial^2 Q_f(q_w, p)}{\partial p \partial q_w} \cdot \frac{\partial q_w}{\partial K}$$

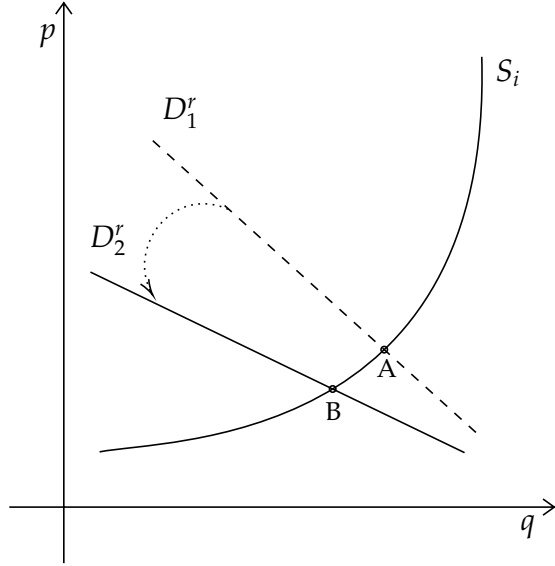
Let $\eta_f = \frac{\partial Q_f(q_w, p)}{\partial p}$ (> 0) denote the slope of aggregate competitor (marginal) fossil fuel generators supply curve. Rearranging,

$$\frac{\partial^2 D_i^r(p, K)}{\partial p \partial K} = - \frac{\partial \eta_f}{\partial q_w} \cdot \frac{\partial q_w}{\partial K} \quad (10)$$

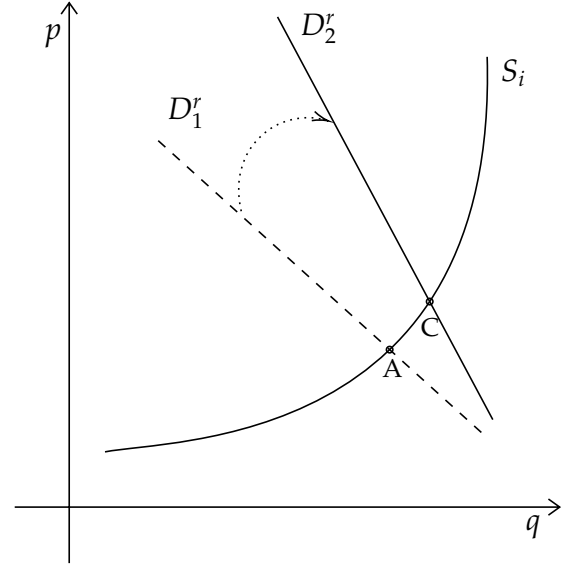
Proposition 3 *The impact of transmission expansion on the elasticity of a marginal generator's residual demand curve is ambiguous.*

The first term on the right hand side in Equation (10) measures the change in the slope of i 's competitors' aggregate supply curve due to an increase in wind generation. Addition of wind capacity and greater market integration could increase the competition and therefore lead to a flatter residual demand curve. This shown in Figure 5a with generator i operating at point B from point A post transmission expansion.

However, higher wind generation could also replace some high cost fossil fuel generators operating at the margin. This would lower the competition amongst fossil fuel generators thereby rotating the residual demand curve as shown in Figure 5b. In this case, generator i moves from point A to point C of its offer curve. Since point C is associated with the steeper region of the offer curve than point A, this enhances its ability to set higher markups.



(a) Anti-clockwise rotation of residual demand curve from D_1^r to D_2^r due to higher market integration



(b) Clockwise rotation of residual demand curve from D_1^r to D_2^r due to replacement of fossil fuel generators at the margin

Figure 5: Rotation of fossil fuel generator's residual demand curve due to transmission expansion.

Therefore, $\frac{\partial \eta_f}{\partial q_w}$ could be weakly positive or negative. This translates to Equation (10) being weakly negative or positive meaning a more inelastic or elastic residual demand curve respectively. Multiplying the inverse of the slope of i 's residual demand curve in Equation (10) gives us the expression for $\Delta \text{Elasticity}$ in Equation (7).

Substituting the expressions for $\Delta \text{Production}$ from Equation (8) and $\Delta \text{Elasticity}$ from Equation (10) in Equation (7):

$$\frac{1}{p - c_i} \cdot \frac{\partial(p - c_i)}{\partial K} = \left[\frac{1}{Q_i^{net}} \cdot \frac{\partial Q_i^{net}}{\partial q_w} + \frac{1}{\partial D_i^r / \partial p} \cdot \frac{\partial \eta_f}{\partial q_w} \right] \cdot \frac{\partial q_w}{\partial K} \quad (11)$$

Equation (11) shows that the overall effect of transmission expansion on generator i 's markup can be broken down into two pieces. First is the effect of wind on generator i 's markups. This is represented by the two terms in the square bracket in Equation (11). Second is the effect of expansion in transmission capacity on wind generation. Equation (11) can alternatively be expressed as:

$$\frac{\partial(p - c_i)}{\partial K} = \underbrace{\frac{\partial(p - c_i)}{\partial q_w}}_{\geq 0} \cdot \underbrace{\frac{\partial q_w}{\partial K}}_{> 0} \quad (12)$$

Thus, the effect of transmission expansion on markups is driven by how wind generation affects markups and the extent to which transmission expansion integrates the electricity generated from wind. From Equation (12), $\frac{\partial q_w}{\partial K}$ simply acts as a multiplier that scales up the effect of wind energy on fossil fuel generator markups.

4.4 Empirical Strategy

In this section, I examine the impact of transmission expansion on fossil fuel generator markups. Equation 12 describes the relationship between transmission lines and markups set by marginal generators. I construct an estimator of the marginal effect of transmission lines on generator markups that is motivated from the theoretical model:

$$\frac{\partial(p - c_i)}{\partial K} = \underbrace{\frac{\partial(p - c_i)}{\partial q_w}}_{\alpha_h} \times \underbrace{\frac{\partial q_w}{\partial K}}_{\beta_h} \quad (13)$$

$(p - c_i)$ is the markup of generator i , K measures transmission expansion, and q_w is the electricity generated from wind. I run the following regressions to estimate the terms on the right hand of Equation 13:

$$y_{it} = \alpha_h \cdot w_t + f(D_t|\lambda) + \kappa_i + \delta_{hmy} + \epsilon_{it} \quad (14)$$

$$w_t = \beta_h \cdot crez_d + \gamma \cdot H_t + \eta_{hm} + \omega_t \quad (15)$$

where, y_{it} is the markup set by marginal generator i at hour t of the sample. Markup is defined as $(p - c)_{it}$ where p is the LMP and c is the marginal cost of generator i at period t . w_t is wind generation (GWh) in hour t , and $crez_d$ is the percentage completion of CREZ transmission project at day d of the sample. The parameters of interest are α_h which measures the impact of wind generation on markups, and β_h which measures the impact of transmission expansion on wind generation.

I use a wide variety of controls to account for potential confounding factors in Equation 14 and Equation 15. I use a quadratic function of system wide electricity demand D_t in Equation 14 to account for variation in markups driven by spikes in electricity de-

mand.¹⁰ In Equation 15, I use the High System Limit (H_t) of electricity generation from wind at hour t to control for the maximum energy production possible from wind at period t .¹¹ H_t is a useful control because it not only incorporates the generating capacity of the wind generator but it also takes into account the real time meteorological conditions that could affect the amount of power generated through wind farms.

As shown in Figure 6 the actual electricity generated from wind w_t closely tracks H_t for each hour from 2011 to 2014. The difference between the two curves for a specific year arises due to the lack of transmission infrastructure needed to transport the power to demand centers. However, with the CREZ expansion in 2013 we see the gap between the high system limit of wind generation and actual wind generation decreasing with the lowest difference observed across all hours of 2014.

To control for unobserved determinants of markups that could be correlated wind generation I use a battery of fixed effects. In Equation 14, I use generator fixed effects (κ_i) to control for any generator specific heterogeneity in markups. I use hour by month by year fixed effects (δ_{hmy}) to control for seasonality exhibited by the electricity market in Texas. This seasonality arises due to varying wind pattern at different hours of the day over the months in a year. For example, wind generation in Texas tends to be higher during the night than during the day. Similarly, wind is typically higher during the spring months than winter and summer months. Similarly, I use hour-by-month fixed effects (η_{hm}) in Equation 15 to control for seasonality in wind generation. ϵ_{it} and ω_t are the random error terms in Equation 14 and Equation 15 respectively.

The identifying variation in Equation 14 comes from the within generator variation in markups caused by changes in wind generation across hours h within a month m in a given year y . For example, α_{16} is the identified from deviations in markups from generator specific averages across all 16:00 hours within a month, in a given year. A similar argument holds for the identifying variation in Equation 15. Under the identifying assumption that control variables and fixed effects account for the confounding factors, α_h captures the unbiased effect of wind generation on generator markups and β_h is the unbiased effect of CREZ expansion on wind generation. Therefore, the hourly estimator

10. Using zonal demand levels instead of system wide demand does not change the results.

11. ERCOT defines HSL for a generation resource as the maximum sustained energy production capability of that entity. HSL is established by the generator itself and is continuously updated in Real-Time.

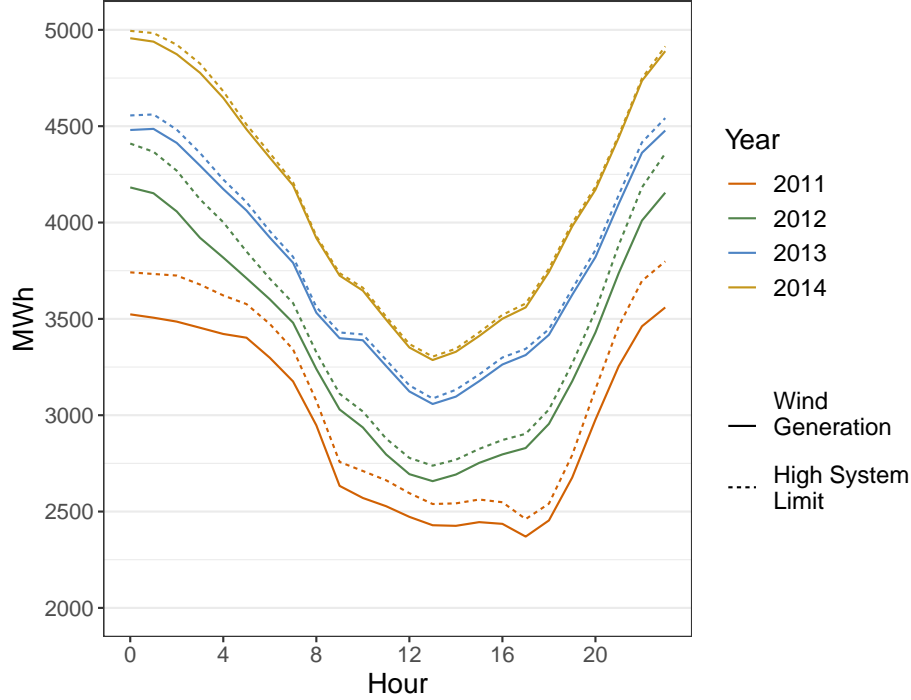


Figure 6: Hourly averages of actual Wind Generation (w_t) and High System Limit (H_t) of wind generation from 2011 - 2014.

Note: H_t is defined as the maximum energy production capability of the generator at period t . It is established by the generator itself and is continuously updated in Real-Time.

of Equation 13 can be written as $\theta_h = \alpha_h \times \beta_h$. Standard errors in Equation 14 are clustered at the generator level. I use Newey West auto-correlation corrected standard errors with a seven day lag structure for estimates in Equation 15.

4.5 Results

I first present the results of the effect of CREZ expansion ($crez_d = 1$) on wind generation in Figure 7 followed by the effect of wind generation on generator markups in Figure 8. The plot of $\hat{\beta}_h$ shows the differential impact of CREZ completion ($crez_d = 1$) on integrating wind generation at hour h . The effect is strongest during the off-peak hours.¹² with the coefficient estimate being the highest at 23:00 and 0:00, about 0.22 GWh. The impact

¹². The peak hours in ERCOT are defined as the hours ending in 7:00 to 22:00 CPT from Monday through Friday. I use this definition to discuss the results of my analysis as well.

of CREZ is least during the peak demand hours with an average of approximately 0.10 GWh between 15:00 - 18:00 hours.

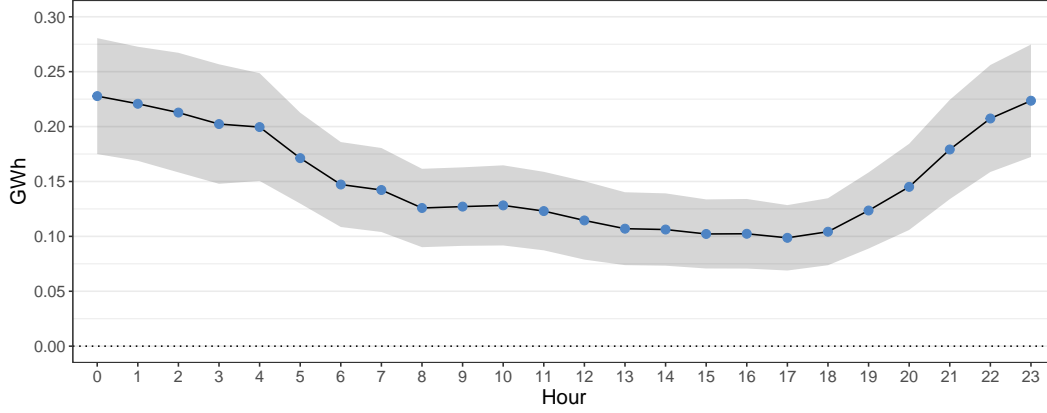


Figure 7: Coefficient estimates ($\hat{\beta}_h$) for the effect of CREZ expansion ($crez_d = 1$) on hourly wind generation (GWh) and the 95 percent confidence intervals.

The hourly pattern of the coefficient estimates ($\hat{\beta}_h$) for the impact of CREZ expansion on wind generation closely follows the hourly wind flow pattern in Texas where the wind flow is strongest during the off-peak hours in the evening compared to the peak hours during the day. This reflects that availability of excess transmission capacity is instrumental in integrating higher levels of wind generation in the Texas electricity market.

Figure 8 shows the coefficient estimates ($\hat{\alpha}_h$) of the magnitude of the decrease in fossil fuel markups (\$/MWh) due to 1 GWh addition of wind energy to the grid. We see that the drop in markups is strongest in magnitude at hour 16:00, about \$9/MWh for 1 GWh of electricity generated from wind. The coefficient estimates are smallest for the off-peak hours. Due to low demand and high electricity generation from wind during the off-peak hours, fossil fuel generators typically operate on a smaller net-demand curve as compared to the net demand during the peak hours.¹³ This lowers their incentives to set high markups during the off-peak than during the peak times. The impact of an additional GWh of wind is therefore higher on the net demand curve during the peak

13. Recall that the net-demand or residual demand curve for fossil fuel generator is defined as $D_i^r(p, q_w; K) = D^S - q_w - Q_f(q_w, p)$ where D^S is the system demand, q_w is the power generated from wind, and $Q_f(q_w, p)$ is the total electricity generated by other fossil fuel generator.

hours than during the off-peak. This is reflected as the larger magnitude of coefficient estimates for the peak hours than for the off-peak hours.

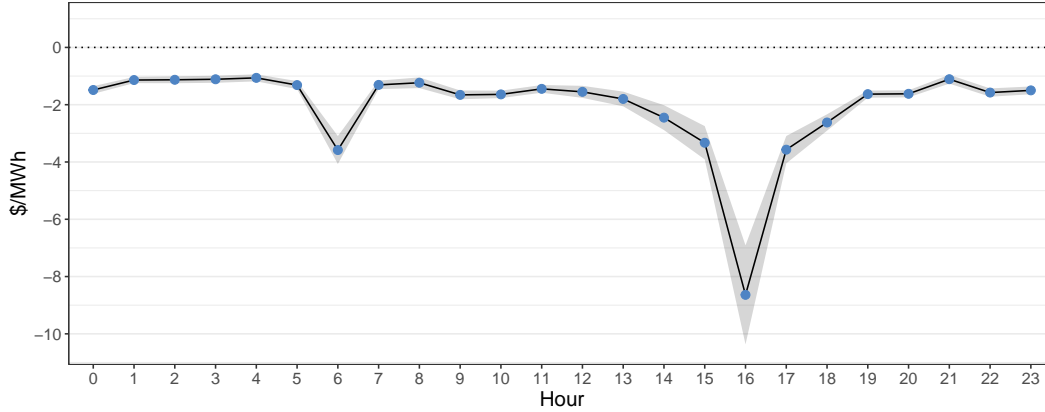


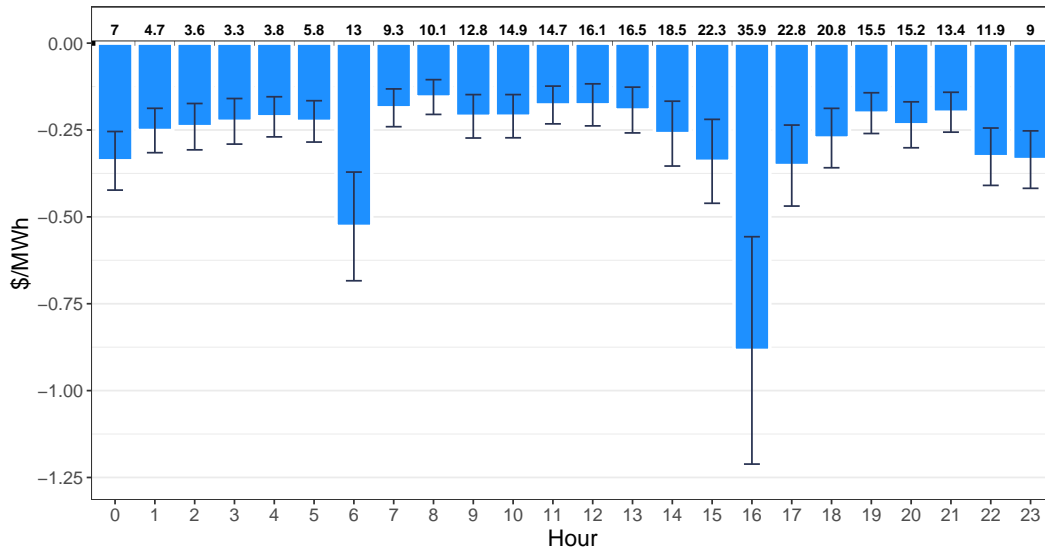
Figure 8: Coefficient estimates ($\hat{\alpha}_h$) for the effect of addition of a GWh of wind energy on generator markups (\$/MWh) and the 95 percent confidence intervals.

I combine the estimates in Figure 7 and Figure 8 to obtain the impact of CREZ on markups ($\hat{\theta}_h$) for each hour in Figure 9a. Results show that the drop in markups due to CREZ is strongest at 16:00, about \$0.88/MWh. This is followed by 6:00 (about \$0.53/MWh) which stands out from other hours in the earlier part of the day possibly because it marks the end of the off-peak hours of weekday in ERCOT. Compared to total wind power integrated at hour 0:00, CREZ only led to the integration of about half that amount at 16:00 (~ 0.10 GWh), but the subsequent drop in markups at 16:00 is about 2.5 times that at 0:00.

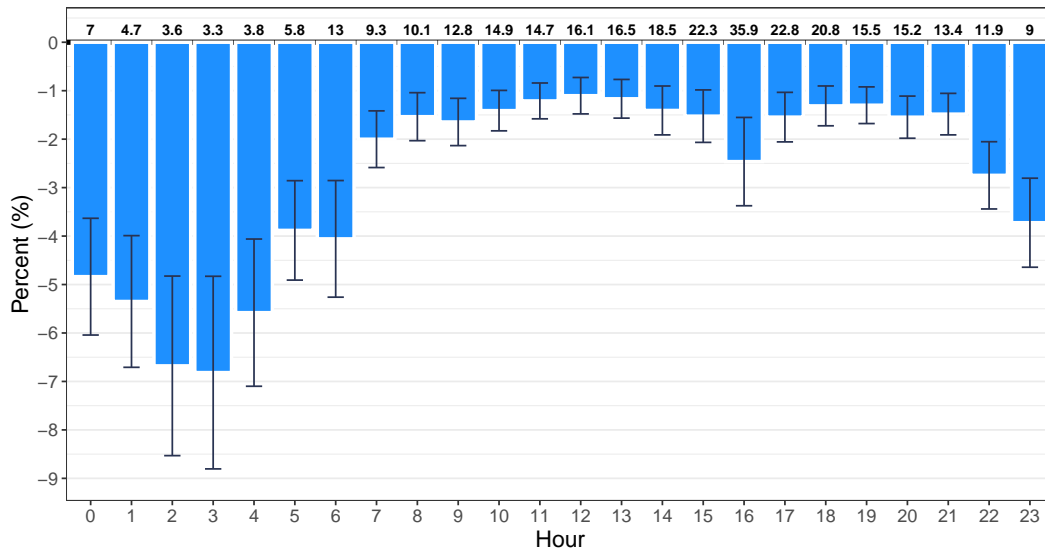
To get a better sense of the magnitudes in Figure 9a, I present the semi-elasticity of markups in response to CREZ expansion (i.e. $crez_i = 1$) in Figure 9b.¹⁴ We see a clear distinction between the semi-elasticity of markups between off-peak v.s. peak hours. The magnitude of the semi-elasticity is highest for hours before 7:00 with the maximum decrease of 6.8 percent at hour 3:00. However, the percentage drop in markups for all peak hours (7:00 to 22:00) is less than 3 percent mainly because of low quantity of wind added to the grid during these hours.

14. I calculate semi-elasticity values by dividing the estimates in Figure 9a with the average markup at each hour.

An important caveat is that the patterns observed in these results are within generator changes in the markups as I use generator fixed effects in Equation 14. A simplified version of this effect is shown in Figure 4 in the theoretical model. In Figure 4b we see an inward shift in generator i 's residual demand curve due to electricity generated from wind. It does not include changes in markups due to generators operating at different points of their supply curve in response to competition from other generators. As shown in the theoretical model, firm exit could incentivize generators to submit steeper offer curves potentially leading to higher markups. I plan to analyze this channel in future work.



(a) Effect of CREZ completion ($crez_d = 1$) on markups (\$/MWh) and the associated 95 percent confidence intervals.



(b) Semi-elasticity of markups for CREZ completion ($crez_d = 1$) and the associated 95 percent confidence intervals.

Figure 9: Short-run impact of CREZ expansion on realized markups.

Note: Average markups for the sample are shown above the x axis.

5 Short-run: Impact of CREZ Expansion on Emissions

How did wind generation due to CREZ expansion affect emissions from the marginal generators in the short-run? The addition of wind generation to the grid would shift the dispatch curve of electricity rightwards. Further, the intermittent nature of wind generation is likely to affect which generator operates at the margin and therefore the marginal emissions. In this section I examine how additional wind generation due to CREZ expansion affected the emissions from the fossil fuel generator(s) operating at the margin at different hours of the day.

The related literature in economics has generally focused on how lower congestion due to transmission expansion affects emissions in the power sector (Fell, Kaffine, and Novan 2021). Any changes in emissions from such an analysis is a result of reshuffling of generation due to lower congestion and integration of wind in the short-run. The analysis in this section attempts to isolate the latter aspect by focusing on the emissions from marginal generators in response to additional wind due to transmission expansion. By conducting the analysis at an hourly level, I am able to estimate the impacts at periods of lower and higher congestion separately.

Looking especially the emissions from marginal generators is useful because of the variation in the types of marginal generators over the course of a day. For example, coal fired generators typically operate at the margin during the night whereas natural gas generators are usually the marginal generators during the day since they are quicker to ramp up or down to meet any sudden changes in demand. This is evident from Figure 10 wherein marginal CO₂ emissions (tons) per MWh of electricity produced are highest during the night and in the early morning.

The addition of wind based electricity to the grid in the night could therefore displace high polluting coal generators from the margin whereas addition of wind energy in the day would potentially displace some natural gas generators. This could lead to higher proportional drop in emissions during the night as compared to the day. To isolate the impact of additional wind energy in the grid on marginal carbon emissions, I estimate the following specification:

$$E_{zt} = \rho_{zh} \cdot w_t + f(D_{zt,t-1}|\lambda) + \alpha_{zy} + \delta_{hmy} + \epsilon_{zt} \quad (16)$$

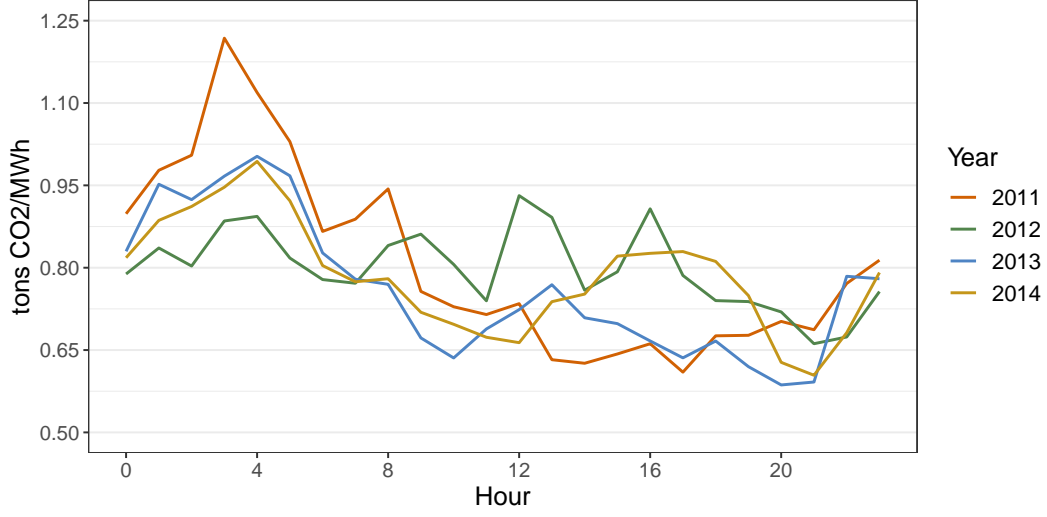


Figure 10: Hourly average of CO₂ emissions (tons) per MWh of electricity generated from marginal fossil fuel generators from 2011 - 2014.

where, E_{zt} is the zonal level marginal emissions (i.e. total zonal emissions from generators at the margin) and w_t is the wind generation at hour t of the sample. The parameter of interest is ρ_{zh} which measures the average impact of an additional GWh of system wide wind generation on the marginal emissions in zone z at hour h .

Marginal generators typically respond to changes in demand of electricity over the course of the day by ramping up or down. I use a cubic polynomial of contemporaneous and lagged demand of electricity $D_{zt,t-1}$ at the zone level to control for the variation in marginal emissions due to changes in the demand. I use zone fixed effect to control for the average emissions level in a zone. Fixed effects δ_{hmy} control for average emission levels at hour h in month m in year y . Conditioning on these averages controls for seasonal patterns in wind generation that could also be correlated with variation in emissions of marginal generators. To account for longer run changes in generation mix of wind capacity, I use zone by year fixed effects denoted by α_{zy} . Standard errors are clustered at the hour-month level to account for serial correlation.

5.1 Results

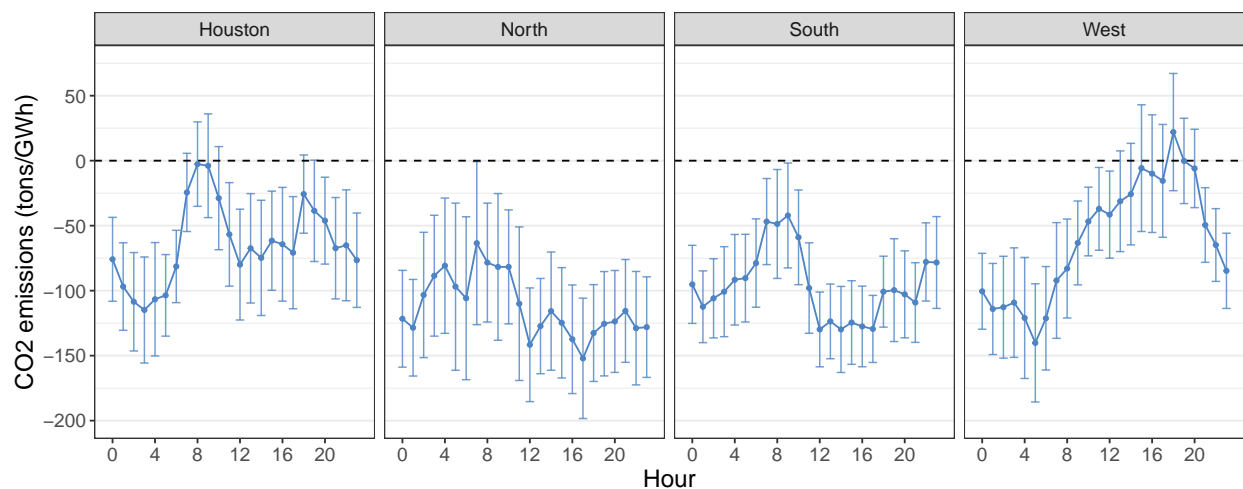
5.1.1 Impact on marginal carbon emissions

Figure 11a shows the average changes in the marginal CO₂ emissions (tons) during each hour of the day across each Zone in response to an additional GWh increase in wind energy. There is a clear decrease in marginal carbon emissions across all the zones throughout the day. However, the hourly pattern of emissions reduction is quite different across the zones. In the North and the South zones the decline is highest in magnitude between the hours 12:00 - 20:00. This pattern is flipped for the West zone wherein the decline is strongest in the night and statistically insignificant for the hours between 12:00 - 20:00. The emission pattern for Houston shares some similarities with the West zone in that the drop in marginal carbon emissions is highest in the night.

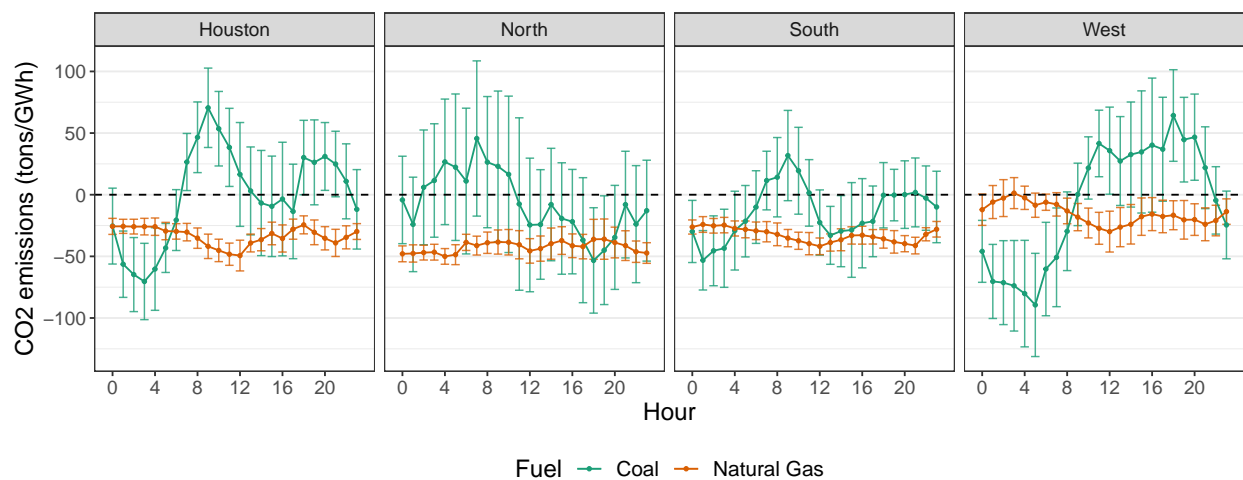
The patterns observed in Figure 11a could be the result of the heterogeneity in the types of marginal generators across the zones at different hours of the day. To explore this, I estimate Equation 16 separately for the sample of marginal emissions from coal and natural gas. The coefficient estimates for impact of wind generation on marginal emissions is shown in Figure 11b. Two key insights emerge. First, the hourly distribution of estimates for coal is very similar to the distribution in Figure 11a, suggesting that the pattern in Figure 11a is mainly driven by emissions from coal generators. Second, the drop in emissions from marginal natural gas generators is mostly stable and negative over the hours across all the four zones. This seems to shift the emissions estimates from coal downwards when aggregated by fuel type giving rise to the pattern in Figure 11a.

Interestingly, the decline emissions from coal generators during the night and early hours of the day suggests that electricity from wind has a significant effect in replacing coal generators from the margin during the night. However, there is a rise in emissions from coal during the early hours of the day especially in Houston and West. This could be a consequence of low wind generation during the early hours of the day leading to higher generation from coal fired power plants.

Zooming in on the marginal generators within West and Houston, we observe that these estimates are driven by the only coal power plants in these zones. In Houston, the coal emissions are due to W.A. Parish Coal Plant (four generators with total capacity of



(a) Impact of additional wind generation (GWh) on marginal CO₂ emissions



(b) Impact of additional wind generation (GWh) on CO₂ emissions from coal and natural gas marginal generators

Figure 11: Short-run impact of wind generation on tons of CO₂ emissions.

2.7 GW) whereas in West the emissions are due to Oklaunion Power Plant (single generator with 720 MW capacity).¹⁵ The increase in carbon emissions in the day suggests that during the periods with low wind generation post 8:00, availability of transmission capacity tends to promote power ramping up of coal generators located near the population centers to meet the demand.

5.1.2 Impact on marginal local pollution (SO₂ and NO_x)

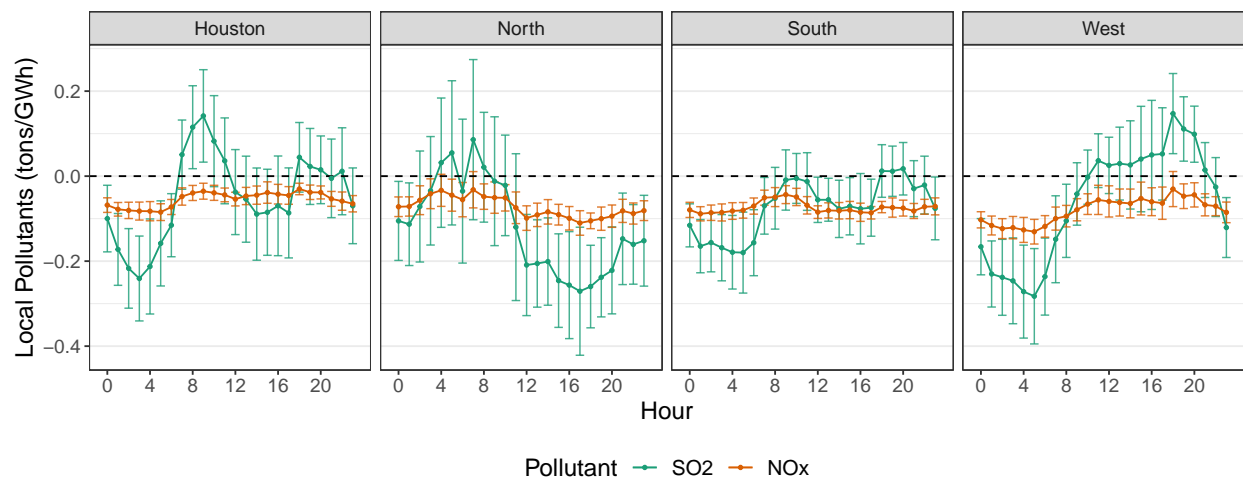
To estimate the impact of hourly wind generation on damages from local pollutants, I use SO₂ and NO_x emissions (tons) from marginal generators as the dependent variable in Equation 16. Figure 12a shows the hourly distribution of coefficient estimates for SO₂ and NO_x. The distribution of the impact of wind generation on tons of SO₂ and NO_x shows substantial variation across the zones and hours of the day. The pattern of SO₂ is very similar to that of carbon emissions from coal generators in Figure 11b.¹⁶ This is because SO₂ is a byproduct from burning of coal in power plants due to the presence of sulphur impurities. SO₂ emissions from natural gas power plants are low because of low amounts of sulphur in pipeline quality natural gas. NO_x on the other hand is released from burning of any fossil fuel due to the mixing of fuel and air (EPA 1998).

Since the impact of local pollutants varies across space due to differences in population, I use estimates of county-specific marginal damages due to SO₂ and NO_x from Holland et al. (2016) to calculate the value of damages due to emissions from each generator. I then aggregate these damages at the Zonal level to estimate Equation 16. Figure 12b shows the coefficient estimates for the damages from SO₂ and NO_x (2020 \$) due to additional wind generation across the zones for each hour of the day.

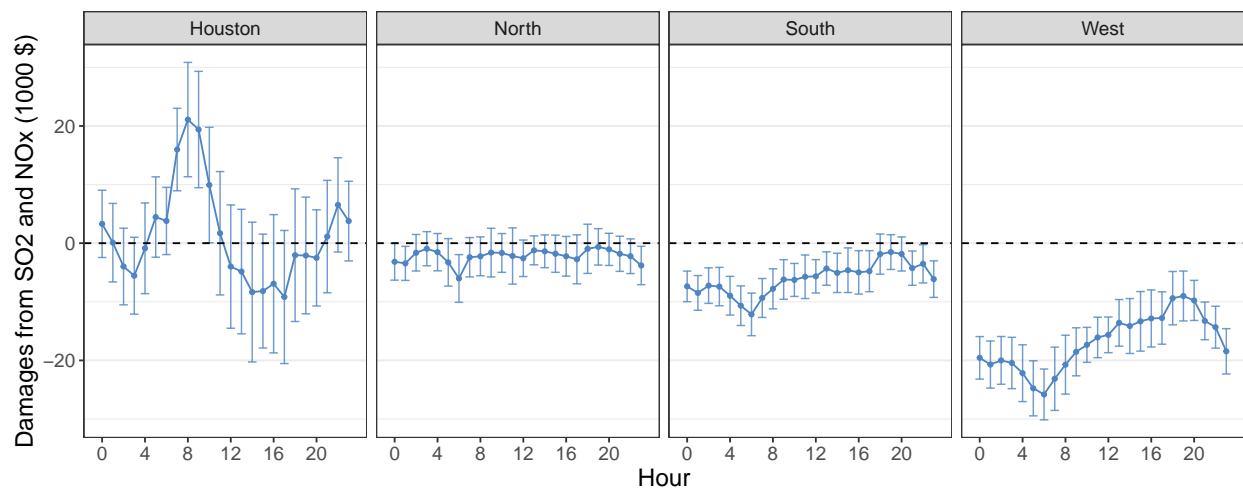
Figure 12b shows evidence of significant heterogeneity in damages avoided from local pollutants across zones. For South and West zones, additional wind leads to decline in damages from SO₂ and NO_x across all hours, whereas the effect is statistically insignificant for the North zone. In case of Houston, we see a significant rise in local emissions during the early hours of the day. This is similar to the rise in carbon emissions observed from the only coal generator W.A. Parish in Houston. It is likely to be driven by ramping

15. Figure B2 in Appendix B shows the location of various coal and natural gas fired marginal generators in the sample from 2011 to 2014 along with ERCOT Zones and CREZ counties.

16. I present the estimates for the effect of wind generation on tons of SO₂ and NO_x from coal and natural gas generators in Figure B3 in Appendix.



(a) Impact of additional wind generation (GWh) on local pollutants (SO₂ and NO_x) in physical units



(b) Impact of additional wind generation (GWh) on damages (2020 \$) from local pollutants (SO₂ and NO_x)

Figure 12: Short-run impact of wind generation on emissions from local pollutants (SO₂ and NO_x).

up of the coal generator during the day when the wind generation becomes low. These ramping effects are shown to undercut the emissions reductions from wind, especially when operating at low levels of efficient generation (Lew et al. 2012).

5.1.3 Damages avoided from marginal emissions

To get a better sense of the magnitudes of hourly marginal emissions, I translate them into average reduction in damages (\$). I combine the hourly ρ_{zh} estimates from Equation 16 with the estimates on average wind generation added to the grid due to CREZ expansion (β_h) from Figure 7. I estimate damages as:

$$D_z(\$) = \sum_{h=0}^{24} \tau \times \beta_h \times \rho_{zh} \quad (17)$$

where, D_z is the zonal daily average of damage (in 2020 \$) due to marginal carbon emissions in zone z . I assume social cost of carbon, τ as \$44 per ton of CO₂ emissions (US Interagency Working Group on Social Cost of Carbon 2014), β_h is the hourly average wind generation added due to CREZ in the short-run estimated in Equation 15, and ρ_{zh} is hourly average of marginal carbon emissions avoided due to an additional GWh of wind energy. For local pollution, I simply multiply the coefficient estimates in Figure 12b with β_h and aggregate over the hours to get the value of average daily damage avoided.

Table 2: Average daily damages (2020 \$) avoided from marginal generators due to CREZ

| Zone | Damages Avoided (2020 \$) | | | Percent (%) |
|---------|---------------------------|-----------------------------------|---------|-------------|
| | CO ₂ | SO ₂ + NO _x | Total | |
| Houston | 11,087 | -6,070 | 5,017 | 3 |
| North | 17,814 | 8,307 | 26,121 | 18 |
| South | 15,133 | 23,210 | 38,343 | 26 |
| West | 11,271 | 63,999 | 75,270 | 52 |
| Total | 55,305 | 89,446 | 144,751 | 100 |

Notes: This table reports the daily average of damages from marginal CO₂ and local pollutants avoided due to additional wind integrated from CREZ expansion for each Zone.

Table 2 reports the average damages avoided (2020 \$) per day from marginal emissions due to CREZ expansion for each zone.¹⁷ We notice that CREZ expansion led to a decline in damages from marginal carbon emissions across all the zones in the short-run. The total damages avoided is about \$55,000 per day with the North and the South zone contributing about three fifths of the total. The distribution of damage reduction across the zones highlights the wide spatial scope of reduction in carbon damages accrued from the integration of wind due to availability of transmission capacity.

The story is a bit different for local pollutants. While the total daily damages avoided is about \$87,000, it is mostly concentrated in the West zone followed by South and North. The negative sign for Houston indicates an increase in damages instead of a decline. This is due to the increase in emissions from W.A. Parish Coal plant in Houston during the day. The total daily damages avoided from carbon, SO₂ and NO_x emissions is \$144,751 which translates to about \$53 million annually.

As shown above, I find that while there is significant spatial and temporal heterogeneity in emissions from marginal generators. While there is an overall decline in emissions, we do observe increase in emissions especially during the periods with low wind generation that lead to coal generators operating at inefficient levels of capacity. This is of significant concern especially in Houston due to the presence of highly polluting coal plants in proximity to population centers.

17. The coefficient estimates of hourly averages of damages avoided for each zone due to CREZ are presented in Figure B4 in Appendix B. The pattern for carbon emissions and local pollution is similar to Figure 11a and Figure 12b respectively.

6 Long-run: Impact of CREZ Expansion on Investment in Wind Projects

In this section I examine whether the counties announced to site CREZ related substations and wind collection points saw higher levels of wind investment. I compile a dataset of all the wind projects in Texas post 2001 using the Wind projects supplement of EIA Form 860. This dataset provides detailed information about a wind project including its location and year of operation. Figure 13 shows the total number of wind projects, total capacity (MW) of projects, and average capacity (MW) per project over 2001 - 2019 in Texas. We see a decline in total projects and total capacity in 2013 possibly due to the expiration of Production Tax Credit (PTC) in late 2012. However, both total capacity and number of projects increased sharply post 2013 with an increasing trend in average capacity per project.

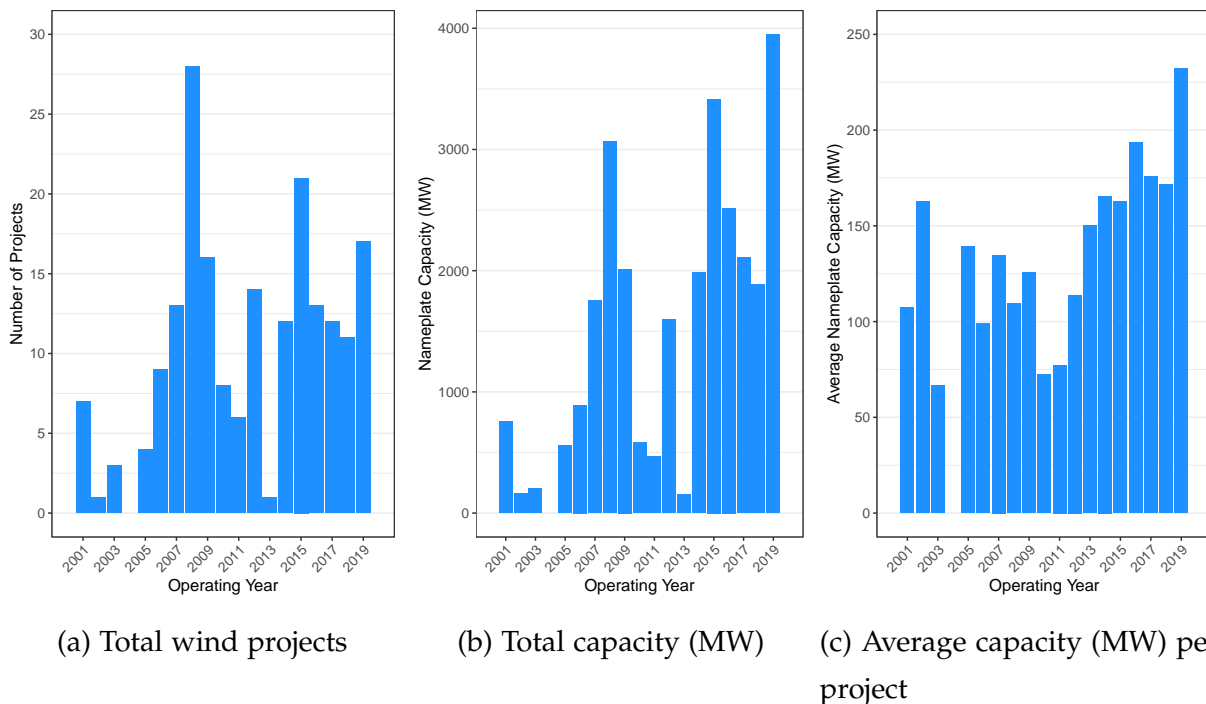


Figure 13: Statistics of wind projects in Texas over 2001 - 2019.

Following the enactment of the Texas Senate Bill 20, the Public Utilities Commission of Texas (PUCT) began the multi-year process of identifying the locations and cost of CREZ expansion project. In April 2008, ERCOT submitted a transmission optimization

study that delineated four scenarios of transmission expansion (ERCOT 2008). Later that year, PUCT selected the second scenario which aimed to accommodate 18.5 GW of electric power by building 3,600 miles of 345 kV electricity transmission lines between existing and new substations throughout the Panhandle, West, and North zones of Texas (PUCT 2009).¹⁸ In the data I only see the counties where these substations were located and thus I refer to these counties as ‘CREZ counties’.¹⁹ I refer to August 2008 as the “announcement date” as it provides the first most accurate information of transmission siting in the CREZ transmission expansion. The specific technical details of the transmission expansion - the cost breakdown, expected completion dates, and various transmission service providers responsible for the expansion was released in October 2010 in CREZ Progress Report (RS&H 2010).

From Figure 14 we can see a cluster of wind projects located within and near CREZ counties post 2010. However, there is also a cluster of wind farms in coastal Texas. This is because of a superior wind quality in this region which could be profitable for wind developers. To parse out whether CREZ counties saw higher levels of wind investment than other counties after accounting for wind quality and other confounding factors, I estimate the following specification:

$$y_{it} = \alpha + \beta \cdot crez_i + \mathbf{X}'\Pi + \epsilon_{it} \quad (18)$$

where, y_{it} is the outcome of interest. I use total wind capacity in county i in year t , average wind capacity of the project (total nameplate capacity/total number of projects in the county), and total number of turbines in county i in year t as the dependent variables for this analysis. The variable $crez_i$ is a binary variable that specifies whether county i is a CREZ county. Since the location details for the CREZ project were initially announced in late 2008, the analysis is restricted to annual county level observations from 2012 through 2019. This allows for the addition of wind capacity in response to

18. Electrical or Transmission substations typically serve as the terminal points for high voltage transmission lines as well as serve as the hub for transmission lines carrying electricity from nearby power generation plants. Therefore, wind farms and other power plants tend to locate near these substations to deliver their electricity.

19. I do not have access to exact location of these substations because it is restricted data for the purposes of national security.

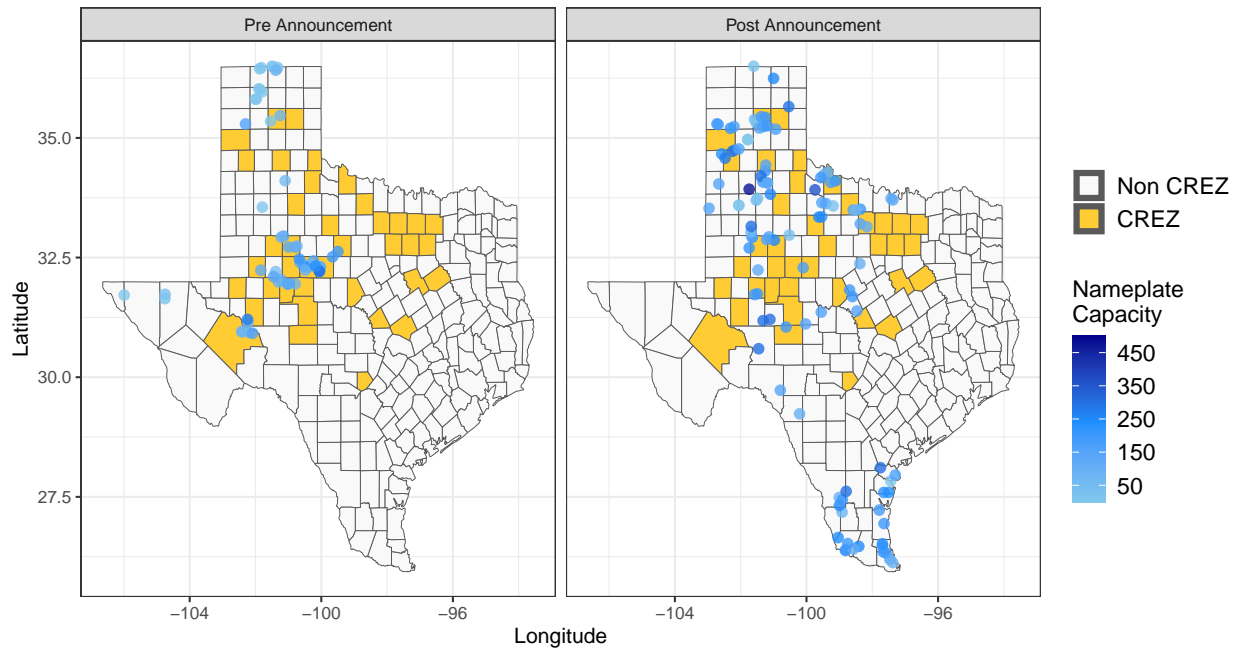


Figure 14: Location and Nameplate Capacity (MW) of wind projects Pre and Post CREZ announcement in August 2008.

Note: This figure shows wind farms in Texas Pre-CREZ Announcement (Jan 2001 - Aug 2008) and Post-CREZ Announcement (Sep 2008 - Dec 2019) samples.

transmission expansion announcement while taking into account the fact that project planning and development typically takes a few years.

I use a battery of control variables and fixed effects summarized by vector \mathbf{X} in Equation (18). I use power curve, capacity factor, and cubic polynomial of average wind speed to flexibly control for wind resource quality of a county. All of these variables come from NREL's Wind Integration National Dataset (WIND) toolkit (Draxl et al. 2015). I use average yearly wind project cost data from Lawrence Berkeley's Wind Technologies Report, land price data, and median land acreage compiled by the Real Estate Center at Texas A&M University to control for project costs.

To control for demographic factors that could influence CREZ transmission siting and location choice for wind projects I use median household income in 2007 and average population over 2007 to 2010. I use average farm size in a county to account for variation in wind investment due to turbine dis-amenities. This is because it is harder to site wind

farms in areas with small farms (Winikoff and Parker 2019). This data comes from the USDA Census of Agriculture. The rationale behind these variables is that counties with higher household incomes, population, or average farm size could have a higher bargaining power in influencing the regulator's decision to site transmission infrastructure and wind farms.²⁰

Cities and counties often enact regulations for wind projects that are sited in their jurisdiction. These regulations are commonly known as setbacks or wind ordinances. They usually specify limits on the size of wind turbines, height of turbines, noise, maximum capacity, etc. The presence of a wind ordinance could affect investment in wind capacity in a county and could also be correlated with siting of transmission infrastructure. I include an indicator variable specifying whether the county (or a city in the county) has a wind ordinance.²¹ I use the publicly available dataset on wind ordinances from WINDEXchange for this variable.

To control for Zone specific characteristics I use Zone fixed effect and cubic polynomial for time trend to control for increasing trend in wind generation across all counties. I use fixed effect for the years 2012 and 2013 to control for a sudden decline in wind installations due to Production Tax Credit (PTC) expiration in late 2012 and the subsequent extension in early 2013. Standard errors are clustered at the county level to account for serial correlation at the county level.

6.1 Instrumental Variable Strategy

A key concern in Equation (18) is the endogeneity of $crez_i$ due to the selection of specific counties for CREZ expansion. This could lead to biased OLS estimate of β . To alleviate this concern I use an instrumental variables strategy with the designation of counties into five Renewable Energy (RE) Zones in 2007 (z_{i2007}) as the instrument. The IV specification can be written as:

20. Household income, population, and average farm size for other years is highly correlated with the 2007 variables that I use in the analysis. Therefore, including values of these variables for other years in the sample does not change the results.

21. Most counties in Texas do not have wind ordinances for large wind projects (i.e. projects bigger than 10 MW). Out of 254 counties, I only find cities in five counties, namely Dallas, Ellis, Kleberg, Taylor, and Wichita to have enacted a wind ordinance for both smaller and bigger wind projects.

$$crez_i = \rho \cdot z_{i2007} + \mathbf{X}'\Gamma + v_i \quad (\text{IV1})$$

$$y_{it} = \alpha + \beta_{IV} \cdot \widehat{crez}_i + \mathbf{X}'\Pi + \eta_{it} \quad (\text{IV2})$$

where, Equation (IV1) is the first stage and Equation (IV2) is the second stage equation.

6.1.1 Identification

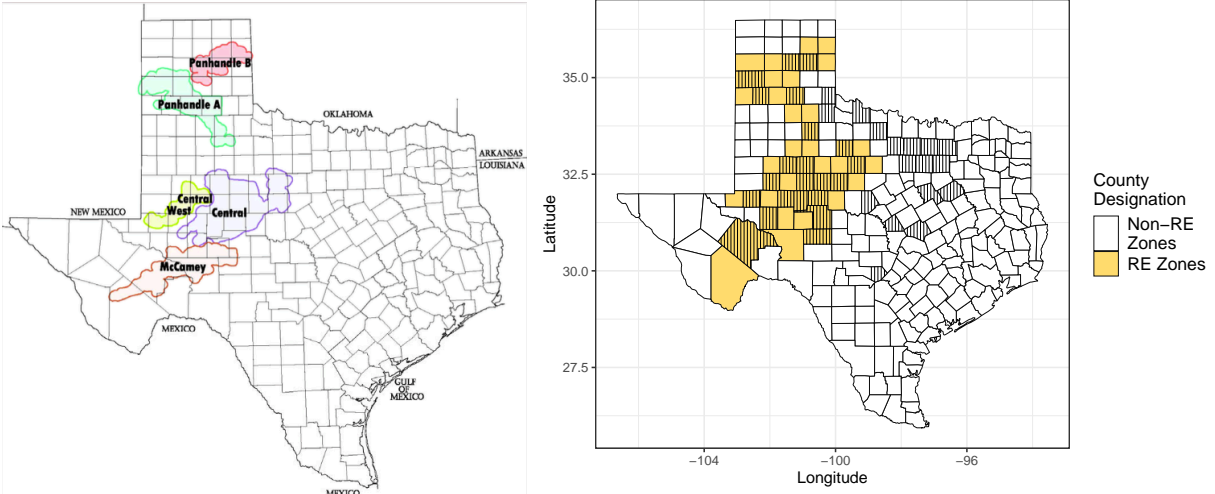
In 2007, the Public Utility Commission of Texas (PUCT or Commission) in its Interim Order on Reconsideration in Docket 33672 designated five zones as Competitive Renewable Energy Zones (PUCT 2007). The five RE Zones - Panhandle A, Panhandle B, Central West, Central, and McCamey are depicted in Figure 15a. These zones were selected based on the existing and potential wind generation capacity, and wind developer interest in these areas. Thus, one of the objectives of the CREZ project was to integrate the wind capacity in these zones to the power grid.

From Figure 15a, I identify the counties that were part of the five RE Zones and denote them as z_{i2007} . These counties are highlighted in yellow in Figure 15b. In April 2008, ERCOT released the CREZ Transmission Optimization Study which analyzed various scenarios for the placement of CREZ transmission lines, substations, and wind collection points within the five RE Zones (ERCOT 2008). Ultimately, scenario 2 was selected by the PUCT as the optimal scenario for CREZ Project. Over the next few years, exact locations of transmission infrastructure was determined based on cost considerations, inputs from county legislatures and wind developers. The hatched counties in Figure 15b are the counties that sited CREZ infrastructure - substations and wind collection points.

As evident from the Figure 15b, there is a significant overlap between the counties that were part of the RE Zones (z_{i2007}) and the CREZ counties ($crez_i$). Therefore, using z_{i2007} as an instrument for $crez_i$ validates the relevance condition:

$$\mathbb{E}[z_{i2007}, crez_i | \mathbf{X}] \neq 0 \quad (19)$$

In words, conditional on the control variables \mathbf{X} , there is a non-zero correlation between a county being designated as a part of the RE Zones and siting transmission infrastructure. Another key aspect of the validity of the instrument z_{i2007} is the exclusion restriction:



(a) RE Zones designation in 2007

(b) Overlap between counties in RE Zones and counties with CREZ substations (hatched).

Figure 15: Designation of counties in Renewable Energy (RE) Zones in 2007 and selection of counties siting CREZ substations in August 2008.

$$E[z_{i2007}, \eta_{it} | \mathbf{X}] = 0 \quad (20)$$

Equation 20 refers to the exogeneity of the instrument to the dependent variable y_{it} . In other words, it implies that conditional on \mathbf{X} , investment in wind energy in a county from 2012-2019 is only driven by its designation to one of the five RE Zones through its effect on the likelihood of that county being selected as a CREZ county.

The exclusion restriction is likely to be satisfied because selection of a site for wind development is a function of numerous factors other than whether it was designated as a CREZ zone. These factors include wind resource quality, location specific costs, wind siting regulations, availability of transmission, and support of the local community. The variables in \mathbf{X} attempt to control for these confounding factors. Further, the main reason for RE Zones was to designate general areas with historically high wind quality where transmission expansion was needed. This was useful in narrowing ERCOT's choice set of identifying possible sites for transmission expansion.

A potential threat to identification which could invalidate the exclusion restriction is that developers with projects within RE Zones prior to 2007 chose to site extensions in the same location post 2012. To address this concern I examine the occurrence of post 2012 extensions for wind projects that started operating before 2007 within RE Zone counties. Figure B1 in Appendix shows that existence of multi-phase wind projects and project extensions are not a cause of concern for the exclusion restriction.

6.1.2 Results

Table 3 reports the results for the OLS and 2SLS regressions of the baseline specification with total nameplate capacity (MW), total turbines, and average capacity per project as the outcome variables respectively. These regressions use the full set of control variables, i.e. time trend, vector of controls for wind resource quality, project cost, county level regulation, demographics, and fixed effects for zone and PTC.

The results for total nameplate capacity suggest a significant increase in wind capacity in CREZ counties. The OLS specification in Column (1) shows that CREZ counties saw an average 43 MW increase in wind capacity than non-CREZ counties. The first stage F-Statistic value for 2SLS regression suggests a strong correlation of the instrument in the First Stage. The coefficient estimate in Column (2) shows that after accounting for confounding factors, CREZ counties have a 62 MW higher wind capacity than non-CREZ counties. The story is the same when total turbines in a county is used as dependent variable. For the 2SLS estimate in Column (4), we see that on an average, CREZ counties have 30 more turbines than non-CREZ counties. All of these results are statistically significant at 5 percent critical level.

Columns (5) and (6) examine whether there is a difference in size of a wind project between CREZ v.s. a non-CREZ county? Controlling for confounding factors, we expect wind developers to build bigger wind projects in sites that have excess transmission capacity and therefore a positive coefficient. However, I find weak evidence in support for this hypothesis. The OLS specification in Column (5) shows that an average project in a CREZ county is about 11 MW bigger than a project in a non-CREZ county. The 2SLS estimate finds this difference to be about 14 MW. However, only the OLS estimate is statistically indistinguishable from a null effect.

Table 3: Effect of CREZ expansion on wind investment - IV results

| | Dependent variable | | | | | |
|-----------------------|-------------------------------|----------------------|----------------------|-----------------------|----------------------------|--------------------|
| | Total Nameplate Capacity (MW) | | Total Turbines | | Avg. Project Capacity (MW) | |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| CREZ | 43.041*** (10.051) | 62.181** (26.786) | 23.358*** (5.149) | 30.285*** (13.596) | 10.620** (4.745) | 14.089 (16.136) |
| Time Trend | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Zone FE | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Wind Controls | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Project Cost Controls | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Regulatory Controls | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Demographic Controls | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| Regression | OLS | 2SLS | OLS | 2SLS | OLS | 2SLS |
| First Stage F-Stat | | 12.842 | | 12.842 | | 12.842 |
| Mean Dep. Variable | 32.939 | 32.939 | 15.866 | 15.866 | 19.911 | 19.911 |
| Observations | 2,024 | 2,024 | 2,024 | 2,024 | 2,024 | 2,024 |
| R ² | 0.218 | 0.216 | 0.206 | 0.205 | 0.196 | 0.195 |

Notes: This table reports the results of OLS and 2SLS regressions for the effect of CREZ expansion on wind investment. The independent variable is a binary variable indicating whether a county is CREZ or not. The instrument for 2SLS regressions is whether a county was designated as one of the five RE Zones in 2007. Sample is a balanced panel of all Texas counties from 2012-2019. Time Trend is a cubic polynomial of time trend variable. Wind Controls include power curve, capacity factor, and cubic polynomial of wind speed (m/s). Project Cost Controls include average wind project cost, real land price, and median land acreage. Regulatory Controls include FE for PTC and wind ordinance in a county. Demographic controls include average farm size (acres) in 2007, median household income in 2007, and average population over 2007 to 2010. Robust Standard Errors reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p< 0.1

6.1.3 Robustness Checks and Caveats

I conduct a series of robustness checks to see how the coefficient estimate of CREZ changes with different combinations of control variables and fixed effects for the OLS and 2SLS specifications. I also restrict the sample to counties in West, Panhandle, and North Zone to discern whether these results are driven primarily by investment in counties within these zones. The results for all the three dependent variables are similar to the estimates reported in Table 3. Appendix C presents the tables for these robustness checks.

Note that the 2SLS estimates in Table 3 are the Local Average Treatment Effect (LATE) of CREZ or the Average Treatment Effect (ATE) for the sub-population of compiler counties. The compiler counties in this case would be the counties that were selected as CREZ because they were part of the RE Zones in 2007, or the counties that were not selected as CREZ because they were not part of the RE Zones. These estimates do not speak to the wind investment in CREZ counties that were selected as CREZ (i.e. $crez_i = 1$) even though they were not part of the RE Zones or the counties that were not selected as CREZ even though they were part of the RE Zones.

Another concern with the instrumental variable strategy is that the counties within the RE Zones were inherently different than the other counties. Table C2 in Appendix shows that counties within RE Zones were statistically different than the other counties on almost all of the observable characteristics pre-transmission expansion announcement. I attempt to account for these factors by including a rich array of control variables that condition on these inherent differences in the counties. However, the concern of a lack of common support amongst the treated and control counties in the 2SLS regressions still remains. Thus, I further address these concerns by implementing a matching estimator which constructs a control group of identical counties based on observable characteristics.

6.2 Matching Strategy

The objective of the empirical strategy in this section is to construct a control group of counties that are comparable to the CREZ counties on the set of observable characteristics. Comparing the counterfactual outcomes from the control group, conditional

on confounding factors would provide the unbiased impact of transmission expansion. However, making a causal claim requires the validity of the conditional independence assumption (CIA). For the context of this paper, CIA can be written as:

$$\mathbb{E}(\epsilon_{it}|\mathbf{X}, \text{crez}_i = 1) = \mathbb{E}(\epsilon_{it}|\mathbf{X}, \text{crez}_i = 0) \quad (21)$$

where, ϵ_{it} is the unobserved component of dependent variable of interest (y_{it}) - wind capacity (MW), total turbines, and average project size. Under the assumption that the unobserved component (v_i) of a county that affects the treatment status is time invariant, using county fixed effect would eliminate the selection bias. However, since the treatment variable is assigned at the county level and at the beginning of the sample, I cannot include county fixed effects.

Instead, I assume that v_i can be approximated using some flexible function of observable county characteristics \mathbf{Z} , i.e. $v_i = f(\mathbf{Z})$. Therefore, validating CIA involves comparing counties with exactly the same combination of characteristics, such that $\mathbb{E}(\epsilon_{it}|f(\mathbf{Z}), \mathbf{X}, \text{crez}_i = 1) = \mathbb{E}(\epsilon_{it}|f(\mathbf{Z}), \mathbf{X}, \text{crez}_i = 0)$. This would provide an estimate of the unbiased effect of the treatment. However, the presence of continuous variables in \mathbf{Z} and a finite sample make it impossible to compare counties based on an exact fit of $f(\cdot)$.

I use Coarsened Exact Matching (CEM) introduced by Iacus, King, and Porro (2012) to obtain the set of counties comparable on observable dimensions which includes both continuous and discrete variables. I divide the sample of counties across CREZ (treated) and non-CREZ (control) groups and then match the counties across the two groups based on observable characteristics using CEM. I use a wide variety of pre-treatment observable covariates to account for factors that could have influenced CREZ siting as well as investment in wind energy post 2012. These factors include historical wind capacity, wind resource quality, average land price and acreage, and demographic characteristics to account for citizen bargaining power (Billo 2017; Cohn and Jankovska 2020).²²

22. Amongst the set of observable dimensions: wind capacity as of 2008, wind speed, capacity factor, average land price over 2007-2010, median land acreage, average farm size in 2007, median household income in 2007, and average population over 2007-2010 are continuous whereas Power Curve and Zone are discrete variables. Each category within Power Curve is matched exactly whereas I use the following structure for exact matching on Zone: {{Panhandle, West}, North, Coastal, Houston, South, None}.

Table 4 provides the balance table of these observable characteristics for pre- and post-matched samples. As evident, CEM provides a well balanced group of treated and control counties that look identical on all observable dimensions. From Table 4 we see that counties that do not lie in the common support of observable characteristics used in matching are discarded from the sample. Therefore, the control group comprises of 30 counties and the treated group comprises of 13 counties. Figure 16 shows the map of treated and control counties. Most of the control counties (light yellow) are adjacent to the treated counties (dark yellow).

For the regression analysis on the counties obtained by matching, I use the same set of control variables as in Equation 18. The key assumption is that conditional on \mathbf{X} , there are no unobservables that affect the outcome variable and treatment status ($crez_i = 1$). Therefore, conditional on \mathbf{X} , the treatment assignment is as good as random for the given set of counties.

Table 4: Balance Table of key observables for Pre- and Post-Matching Sample

| Variables | Pre-Matching | | | Post-Matching | | |
|-------------------------------|---------------|---------------|---------|---------------|---------------|---------|
| | Means Treated | Means Control | p-value | Means Treated | Means Control | p-value |
| | [CREZ = 1] | [CREZ = 0] | | [CREZ = 1] | [CREZ = 0] | |
| Wind Capacity as of 2008 (MW) | 158.599 | 5.579 | 0.000 | 5.581 | 4.264 | 0.138 |
| Wind Speed (m/s) | 7.923 | 7.348 | 0.000 | 7.887 | 7.891 | 0.619 |
| Capacity Factor | 0.449 | 0.413 | 0.000 | 0.437 | 0.439 | 0.949 |
| Power Curve = 1 | 0.000 | 0.005 | — | 0.000 | 0.000 | — |
| Power Curve = 2 | 0.692 | 0.393 | — | 0.837 | 0.837 | — |
| Power Curve = 3 | 0.308 | 0.603 | — | 0.163 | 0.163 | — |
| Avg. Land Price (2007-2010) | 284.684 | 424.427 | 0.000 | 228.424 | 231.216 | 0.929 |
| Median Land Acreage | 560.184 | 779.632 | 0.032 | 360.746 | 351.736 | 0.161 |
| Zone: Coastal | 0.000 | 0.051 | — | 0.000 | 0.000 | — |
| Zone: Houston | 0.000 | 0.028 | — | 0.000 | 0.000 | — |
| Zone: None | 0.000 | 0.107 | — | 0.000 | 0.000 | — |
| Zone: North | 0.308 | 0.220 | — | 0.163 | 0.163 | — |
| Zone: Panhandle | 0.179 | 0.136 | — | 0.302 | 0.371 | — |
| Zone: South | 0.026 | 0.252 | — | 0.000 | 0.000 | — |
| Zone: West | 0.487 | 0.206 | — | 0.535 | 0.466 | — |
| Avg. Farm Size in 2007 | 1,595.667 | 1,724.206 | 0.418 | 1,183.140 | 1,262.035 | 0.118 |
| Median Income in 2007 | 43,133.130 | 39,739.930 | 0.000 | 35,789.190 | 35,574.620 | 0.837 |
| Avg. Population (2007-2010) | 171,282.000 | 83,280.770 | 0.002 | 28,917.870 | 20,612.030 | 0.026 |
| Total Units | 312 | 1,712 | | 104 | 240 | |

Notes: This table presents balance test of key pre-treatment observable characteristics of a county. Each unit is a county-year observation. Pre-Matching sample includes all county-year observations. Post-Matching sample is selected using Coarsened Exact Matching (CEM).

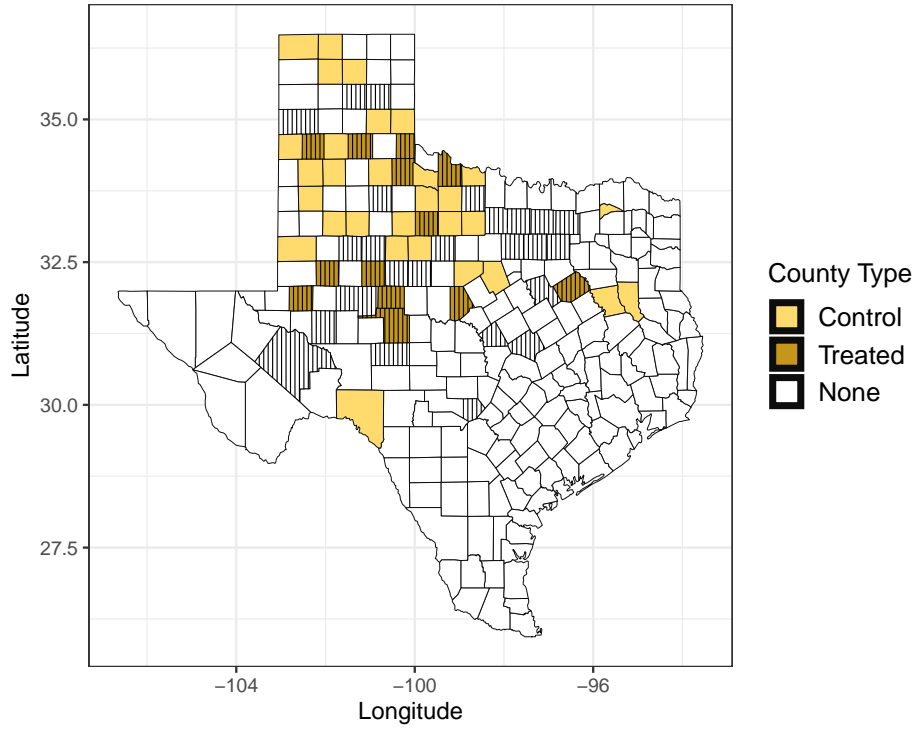


Figure 16: Treated and Control counties obtained using Coarsened Exact Matching (CEM). Hatched counties depict the original CREZ counties.

6.2.1 Results

Table 5 reports the regression results of the baseline specification with total nameplate capacity (MW), total turbines, and average project capacity (MW) as the dependent variables respectively. All the specifications include the same set of control variables used in the IV strategy. I include the interaction of matched group fixed effects with the time trend to allow for unobserved factors that could affect specific groups and vary over time. The sample is a balanced panel of 13 treated and 30 control counties obtained using CEM.

Column (1) in Table 5 shows that the counties that received CREZ expansion on an average saw approximately 73 MW higher wind capacity than the control counties. This result is about 10 MW higher than the IV estimate and about 30 MW higher than the OLS estimate highlighting the presence of counties outside the common support in both of those cases. In a similar vein, Column (2) shows that treated counties on an average had

about 40 more turbines than the control counties. This is 10 turbines more than the IV estimate in Table C6. Similar to the earlier results on average project size, coefficient estimate in Column (3) lends weak evidence to the hypothesis that wind projects in CREZ counties were bigger than the projects in non-CREZ counties. The estimate implies that on an average wind projects in CREZ counties were about 33 MW bigger than projects in non-CREZ counties.

6.2.2 Robustness Checks

I conduct a series of robustness checks to see how the coefficient estimate of CREZ changes with different combinations of control variables and fixed effects. Specifically, I show how the results change when only using group fixed effects with and without CEM weights. The results for all the three dependent variables are similar to the estimates of baseline specification reported in Table 5. Appendix C presents the tables for these robustness checks.

The analysis in this section provides robust causal evidence on addition of wind capacity due to transmission expansion. I consider matching strategy as the preferred empirical strategy for the long-run estimates. The results imply that the semi-elasticity of a county getting CREZ substations was 202 percent higher wind capacity, 245 percent more wind turbines, and 121 percent bigger wind projects over the period of 2012 to 2019. In order to contextualize these estimates, I conduct a back of the envelope calculation.

By the end of 2019, Texas had about 26 million electricity consumers and a total wind capacity of about 23.860 GW (ERCOT 2020). Taking the average number of people per household in Texas in 2019 as 2.85 (US Census Bureau 2020), total households served by ERCOT in 2019 was about 9.122 million. ERCOT estimates that on an average, 1 MW of electricity can power about 200 Texas households during the periods of peak demand (ERCOT 2020). Using the capacity factor of 40 percent for 2019 (EIA 2020), wind generators in Texas could power about 21 percent of total households at peak demand. With 73 MW of capacity added per CREZ county, I find that wind added due to CREZ expansion could power about 2.6 percent of total households in 2019.

Table 5: Effect of CREZ expansion on wind investment - matching results

| | Dependent variable | | |
|-----------------------|----------------------------------|-----------------------|------------------------------------|
| | Total Nameplate Capacity (MW) | Total Turbines | Avg. Capacity of a project (MW) |
| | (1) | (2) | (3) |
| CREZ | 72.640*** (26.499) | 39.419*** (13.075) | 32.756* (19.093) |
| Time Trend | ✓ | ✓ | ✓ |
| Wind Controls | ✓ | ✓ | ✓ |
| Project Cost Controls | ✓ | ✓ | ✓ |
| Regulatory Controls | ✓ | ✓ | ✓ |
| Demographic Controls | ✓ | ✓ | ✓ |
| FE | Group × Trend | Group × Trend | Group × Trend |
| Sample | Matched | Matched | Matched |
| CEM Weights | ✓ | ✓ | ✓ |
| Mean Dep. Variable | 35.907 | 16.067 | 26.951 |
| Observations | 344 | 344 | 344 |
| R ² | 0.467 | 0.476 | 0.426 |

Notes: This table reports the result of baseline regressions on the matching sample. The sample is a balanced panel of 13 treated (CREZ) and 30 control (non-CREZ) counties from 2012-2019 obtained using CEM. The independent variable is a binary variable indicating whether a county received CREZ transmission infrastructure or not. Time Trend is a cubic polynomial of the time trend variable. Wind Controls include power curve, capacity factor, and cubic polynomial of wind speed. Project Cost Controls include average wind project cost, real land price, and median land acreage. Regulatory Controls include FE for PTC and wind ordinance in a county. Demographic controls include average farm size (acres) in 2007, median household income in 2007, and average population over 2007 to 2010. Robust Standard Errors clustered at the county level reported in parenthesis. Significance: ***p<0.01;**p<0.05;*p<0.1

The key assumption in the calculation above is that wind generators in Texas operated at a capacity factor of 40 percent throughout 2019. However, there is substantial variation in capacity factor within Texas over a year. For example, capacity factor of wind farms in Texas in 2019 varied from 44 percent in windier spring months to about 35 percent in other months (EIA 2020).

7 Discussion and Policy Implications

Efforts to combat climate change in the US have largely focused on building generating capacity using solar and wind energy. A key factor in ensuring that the power generated through these sources is fully utilized is the availability of transmission capacity that could carry the electricity to demand centers. According to Larson et al. (2020), US needs to triple its transmission infrastructure in order to decarbonize by 2050. The grid failure in Texas due to the winter storms in February 2021 has also renewed calls for grid expansion so as to integrate various electricity markets in the US (Plumer 2021; Campbell 2021).

Using the CREZ transmission expansion in Texas as the case study, this paper provides evidence of the short- and long-run impacts of large scale grid expansion. For the short-run, I examine the impact of grid expansion on the markups and emissions from fossil fuel generators operating at the margin of the dispatch curve. I write a theoretical model to fix intuition on how transmission expansion affects generator markups in my empirical setting. The model lends itself to the empirical strategy in the sense that I am able to derive an estimator measuring the impact of CREZ expansion on realized markups. This estimator proceeds by first measuring the impact of wind generation on markups followed by the impact of CREZ on integrating existing wind capacity to the grid in the short-run.

I use a fixed effects model to estimate the empirical analogues of the estimator derived in the theoretical model. Keeping generating capacity fixed, I find that CREZ led to the integration of about 0.10 - 0.22 GWh of wind energy into the grid in the short-run. This in turn had a moderate effect on lowering markups set by fossil fuel generators. I

find that CREZ expansion on average led to a decline in markups by about 2.5 percent during peak demand hours and 7 percent during off-peak hours.

The short-run analysis finds that CREZ expansion prevented about \$53 million (2020 \$) worth of annual damages from marginal emissions. About 60 percent of the damages avoided are from local pollutants (SO₂ and NO_x) with the remaining share from carbon emissions. The analysis reveals an increase in carbon emissions and local pollutants as a result of ramping up of coal generators at the margin due to wind intermittency during the early hours of the day. This is most pronounced for the marginal coal generators in the West and Houston. Further, availability of excess transmission capacity during the periods of low wind exacerbates the damages from emissions from these generators.

Next, I examine if grid expansion spurs investment in wind energy in the long-run. I use an instrumental variables and matching strategy to analyze the impact of CREZ expansion on wind investment. The IV estimates suggest that on an average CREZ led to about 62 MW (+189%) higher wind capacity in treated counties. I use coarsened exact matching to address the support problem in 2SLS regressions and obtain a comparable group of 30 control and 12 treated counties. OLS regressions on the matched sample suggests that CREZ counties saw a 73 MW (+202%) increase in wind capacity over 2012-2019. Further, I find weak evidence that wind projects in treated counties were about 33 MW (+121%) bigger than wind projects in control counties.

The results in this paper have several policy implications. First, the short-run results highlight the role of technologies like grid-scale energy storage in mitigating some of the negative impacts of wind intermittency. Grid-scale storage can be used to reduce curtailment of wind and use that electricity at peak demand hours when the wind generation is low. In case of markups, this can be useful in lowering markups at the peak hours and in turn enhance the impact of transmission expansion. Grid-level energy storage can also address the rise in emissions from ramping up of coal generators due to wind intermittency. This is especially significant in addressing emissions from coal generators located near high population centers like Houston.

Second, the results in this paper speak to the potential impacts of large scale grid expansion projects in other parts of the US. For instance, dropping out of thousands of megawatts of renewable energy projects from development due to inadequate transmission capacity in the Midcontinent ISO (MISO) has prompted calls for grid expansion and reforms (Thill 2020). MISO recently launched the Long-Range Transmission Planning Initiative in order to address some of these concerns (MISO 2020). Further, adequate transmission capacity would be required in order to avoid congestion due to growing wind investment in parts of Iowa that are far from the demand centers.

Third, the impacts of grid expansion highlight the need for investments in grid resilience and upgrades. This is because growing wind capacity can put a strain on the existing transmission capacity thereby undoing some of the gains of transmission expansion. The impacts of such investments are particularly salient during the periods of temperature shocks that can lead to congestion and wind curtailments to maintain grid reliability. These curtailments can also undo some of the estimated short-run gains from transmission expansion.

Finally, this paper highlights the potential inefficiency in investment in wind energy, especially due to over-investment in certain regions leading to curtailment. Atal (2020) studies this issue and finds evidence of inefficiency in the timing and location of wind investments in the US. In another paper, I extend this idea to study the inefficiency due to localized over-investment in wind energy in sites that receive transmission investment. Such inefficiencies in investment can undo some of the gains seen from transmission expansion.

These findings open up several avenues for future research. A key issue with renewable sources is their intermittency. Grid-scale energy storage can be a useful step to address some of the concerns highlighted in this paper. However, more research is needed to understand the market impacts of grid level storage and the incentives necessary to investment in this technology. Karaduman (2020) is an important first empirical analysis in this direction. Using a dynamic equilibrium model, the author finds heterogeneous impacts of grid-level storage on the returns from renewable production and the need for a capacity market to incentivize private players to invest in storage.

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Appendix

A Data Sources and Sample Construction

A.1 Data and sample for markup analysis

In this section, I describe the sample construction for the short-run analysis. The hourly generator level sample used in the short-run analysis on the effect of CREZ expansion on markups uses data from three sources - ERCOT Report 13029, EIA Form 860, and EPA's CEMS Data. A brief description of these data sources is as follows:

ERCOT Report 13029 This report includes the offer price and the name of the entity submitting the offer for the highest-priced offer selected or dispatched by the Security Constrained Economic Dispatch (SCED) two days after the applicable operating day. It identifies all the entities that submitted the highest-priced offers selected for each SCED run (in case of multiple entities). SCED is the market clearing process in ERCOT and occurs at every 15 minutes. Therefore, this data is at 15 minute intervals for August 2011 to December 2014. I aggregate this data at the hourly level and all the generators that appear in this data in a specific hour are regarded as marginal generators for that hour. Apart from the identity of the generation resource, this dataset also includes the Locational Marginal Price (LMP) resolved at the resource node for that generator. This acts as the wholesale price corresponding to the marginal generator.

EIA Form 860 This is an annual dataset of all the power plants and generators operating in the US. This data contains information like EIA code of the power plant and generator(s), plant name, location, generator technology, prime mover, main energy source, regulatory status of the power plant, nameplate capacity, operating month and year, planned retirement year, operating status etc.

CEMS Data This is an hourly level data of all the fossil fuel generators at least 25 MW in size. It contains information on hourly emissions (CO_2 , NO_x , and SO_2), hourly generation, and heat input. The generators are identified using ORISPL Code.

For my sample period, ERCOT Report 13029 contains about 300 fossil fuel generators that operate at the margin at some instance. Since I do not observe the EIA Plant Code or Generator ID in ERCOT Report 13029, I manually match each of the 300 fossil fuel

generators to the corresponding generators in the EIA Form 860. I am able to successfully match most of the generators in the ERCOT data to EIA Data.

The next part of sample construction is to match the generator data in EIA to hourly generator data in CEMS. The generator identifiers in CEMS are the ORISPL Code and Unit ID. ORISPL Code corresponds directly to the EIA Plant Code for most cases. I verify and correct ORISPL Codes in case of any discrepancy. Similarly, Unit ID in CEMS data corresponds directly to generator id in EIA Form 860. However, I verify and correct all the cases where there is any discrepancy.

A.2 CREZ Transmission Expansion Data

I use Transmission Project Information Tracking (TPIT) Reports obtained from ERCOT to assemble the dataset on CREZ transmission expansion. These reports contain detailed information on various electricity transmission projects in Texas. I specifically focus on new transmission lines built as a part of CREZ project. These reports provide the length of each transmission line (in miles) along with their in-service dates. I also see the counties where the terminals of each specific line lies. These terminals are usually existing or new electrical substations. The data on the exact location of these substations is restricted since it is considered a matter of national security, thus, I only see the county where these substations are located.

B Supplementary Figures

B.1 Existence of multi-phase wind projects and project extensions

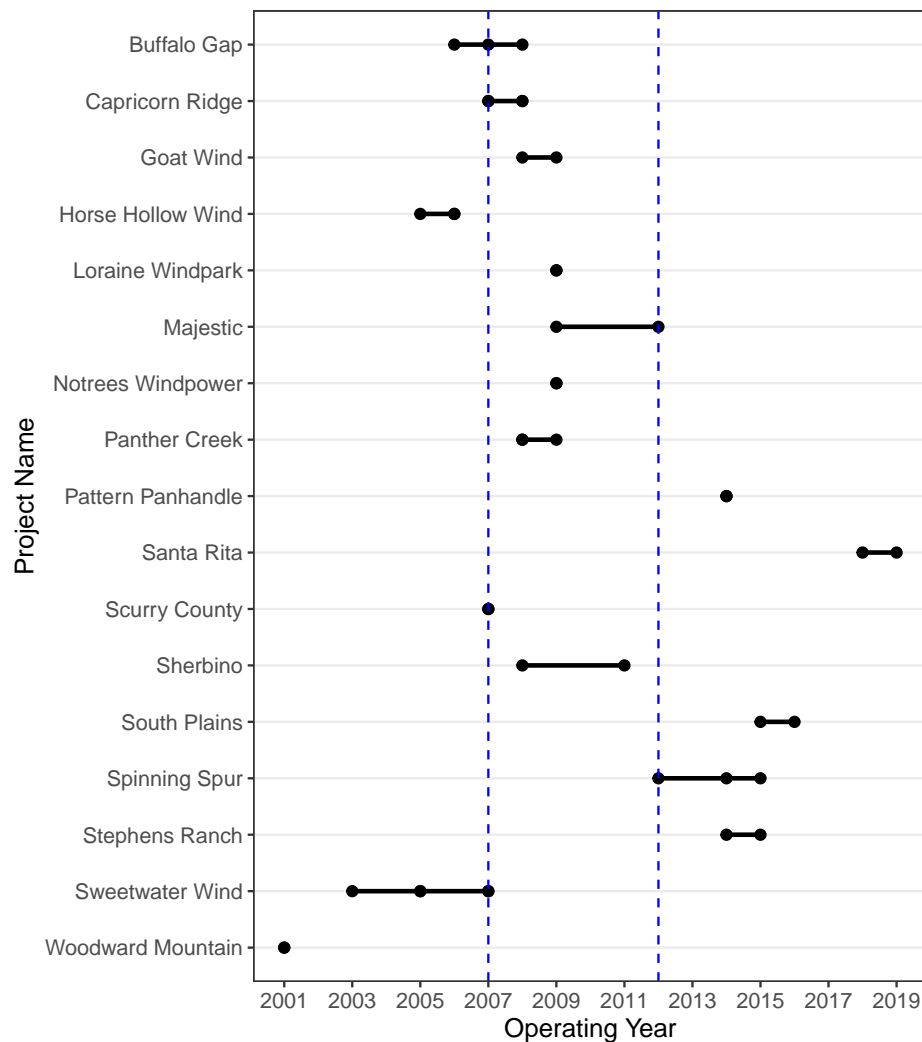


Figure B1: Wind projects with multiple phases and extensions

Note: This figure presents projects with multiple phases or extensions. Each dot represents at least one phase. Projects with single dots (like Loraine Windpark, Notrees Windpower etc.) have multiple phases completed in the same year. There are 43 individual projects within 17 “main projects”. The exclusion restriction would be violated if a line segment intersects both the dotted vertical lines for the years 2007 and 2012. From the figure, we do not see any instance of such a situation. However, wind projects under Majestic 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 RE Zone designation in 2007 and only the second phase is counted in the dependent variable(s).

B.2 ERCOT Zones, marginal generators, and CREZ Expansion

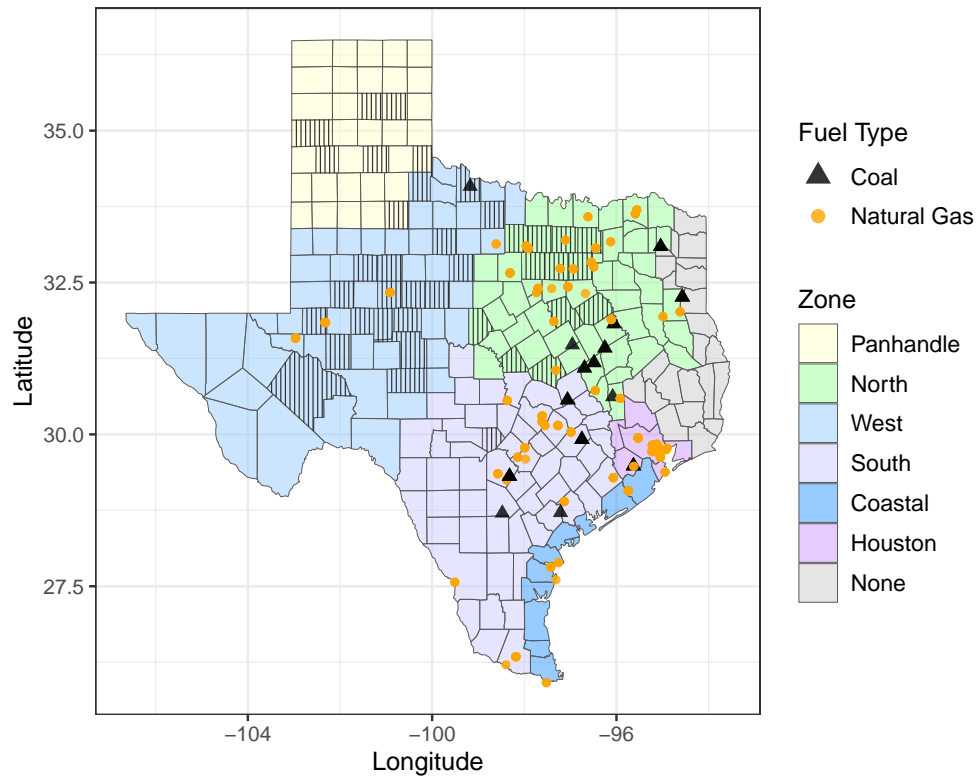
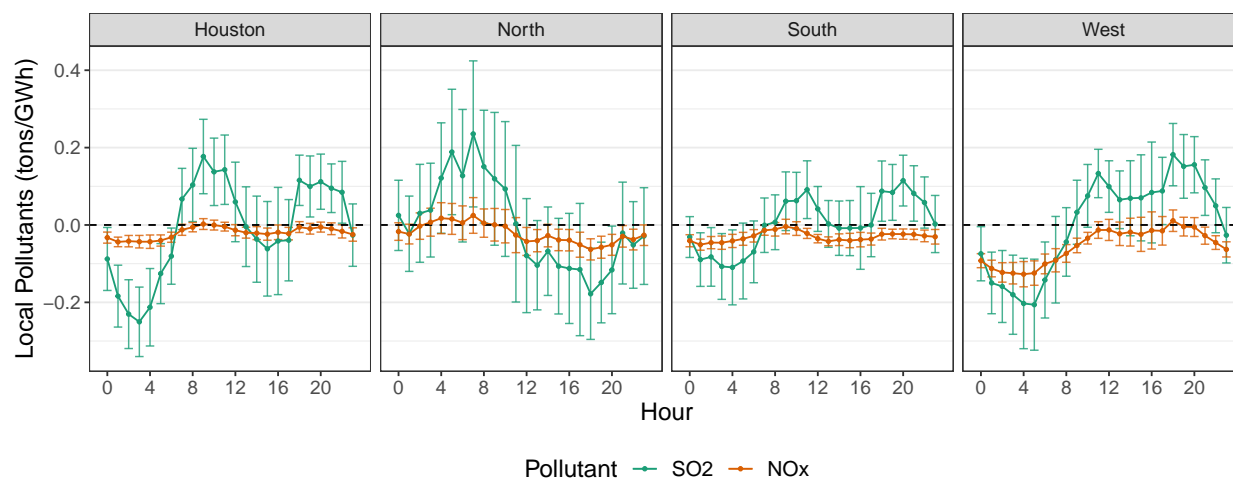
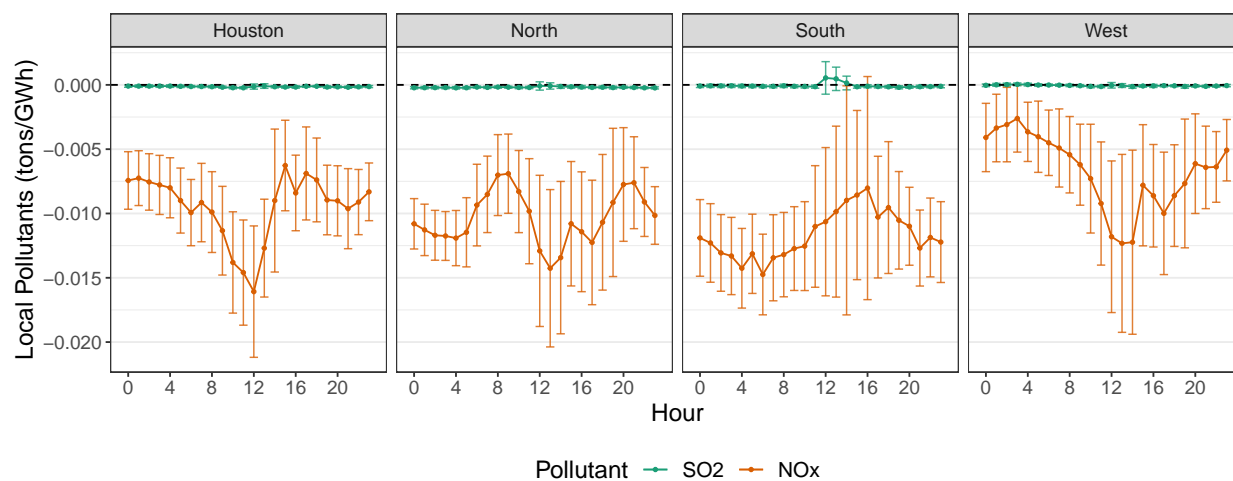


Figure B2: Coal and natural gas fired generators operating at the margin in sample from 2011 - 2014. Hatched counties denote the counties that received CREZ transmission expansion.

B.3 Wind generation and local pollution from marginal generators



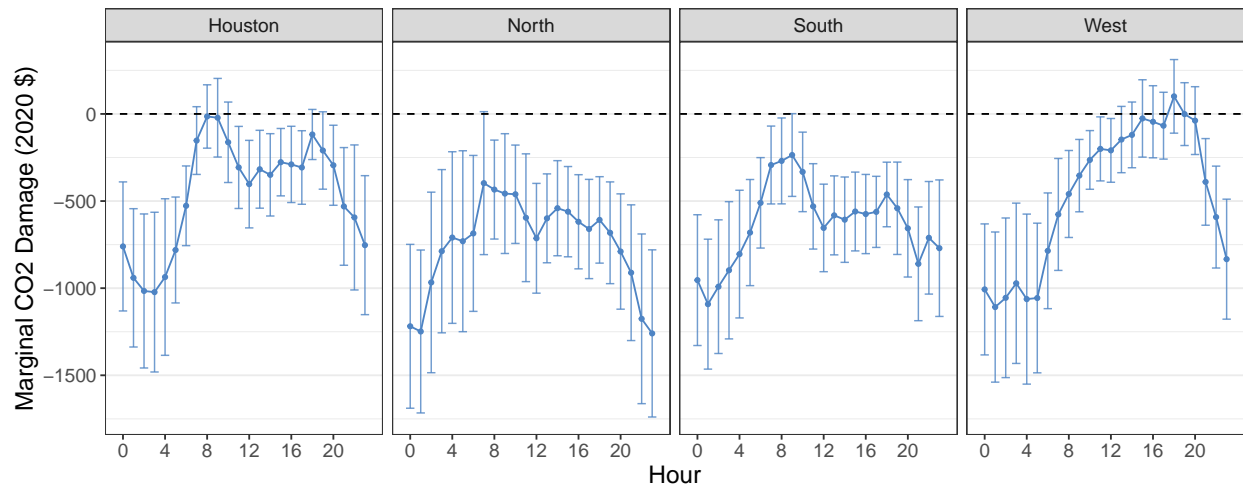
(a) Impact of wind generation on local pollutants (SO₂ and NO_x) from coal generators



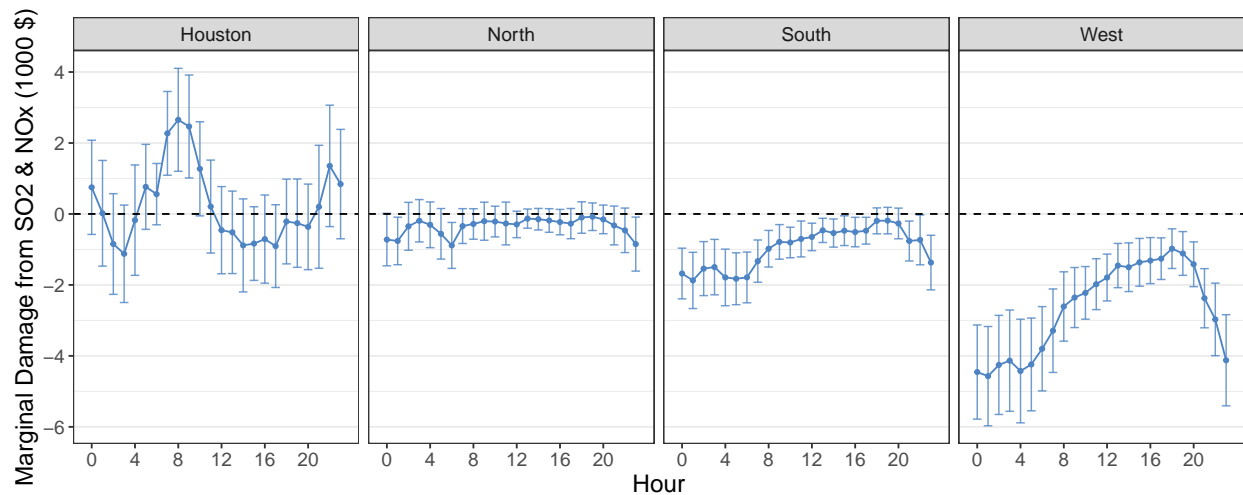
(b) Impact of wind generation on local pollutants (SO₂ and NO_x) from natural gas generators

Figure B3: Short-run impact of wind generation on local pollutants (SO₂ and NO_x) by generator type

B.4 Marginal damage estimates from CO₂ and local pollutants for each hour



(a) Damages due to global pollution (CO₂)



(b) Damages due to local pollution (SO₂ and NO_x)

Figure B4: Hourly averages of the marginal damages (2020 \$) avoided due to CREZ expansion for each zone over 2011 - 2014.

C Supplementary Tables

C.1 Descriptive Statistics

Table C1: Descriptive statistics of key variables used in the short-run analysis of the effect of CREZ on fossil fuel generator markups

| Variable | 2011 | | 2012 | | 2013 | | 2014 | |
|------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| Marginal Cost (\$/MWh) | 17.19 | 14.13 | 12.97 | 12.16 | 18.48 | 17.88 | 20.71 | 19.39 |
| Markups (\$/MWh) | 12.20 | 33.10 | 12.76 | 41.79 | 12.15 | 76.53 | 12.59 | 36.09 |
| Load (GWh) | 35.30 | 8.24 | 36.16 | 7.59 | 37.02 | 7.62 | 38.05 | 7.93 |
| Wind Generation (GWh) | 2.47 | 1.59 | 2.96 | 1.73 | 3.30 | 1.95 | 3.88 | 2.43 |
| CREZ progress | 0.06 | 0.01 | 0.11 | 0.06 | 0.61 | 0.22 | 1 | 0 |

This table reports the annual means and standard deviation (SD) of key variables used in the short-run analysis in Section 4. Note that marginal cost and markups is at the hourly generator level, load and wind generation are the hourly system level. CREZ progress is the ratio of cumulative addition of transmission lines (at the daily level) to total length of transmission lines built in CREZ.

Table C2: Difference in means test of key observable characteristics of counties within and outside CREZ Zones

| Variable | Not in CREZ Zones ($z_{i2007} = 0$) | Within CREZ Zones ($z_{i2007} = 1$) | p-value |
|-------------------------------|--|--|---------|
| Wind Resource Quality | | | |
| Wind Speed (m/s) | 7.281 | 8.085 | 0.000 |
| Capacity Factor | 0.413 | 0.442 | 0.000 |
| Power Curve | 2.672 | 2.061 | 0.000 |
| Project Cost Variables | | | |
| Median Land Acreage (acres) | 724.720 | 993.122 | 0.038 |
| Real Land Price | 313.567 | 119.592 | 0.000 |
| Avg. Annual Project Cost | 1,759.884 | 1,759.884 | 1.000 |
| Wind Regulation | | | |
| Wind Ordinance | 0 | 0 | — |
| Demographic Variables | | | |
| Avg. farm Size 2007 | 1,487.549 | 2,607.163 | 0.000 |
| Population | 105,193.300 | 20,974.870 | 0.000 |
| Median Income in 2007 | 40,461.870 | 39,435.020 | 0.011 |

This table reports the difference in means test of key observable characteristics of counties within ($z_{i2007} = 1$) and outside ($z_{i2007} = 0$) the five CREZ Zones. To highlight the pre-existing differences in the counties, all the observations are pre-transmission expansion announcement. Avg. Annual Project Cost is the capacity weighted average project cost in \$/kW and is common across all counties for a given year. Wind Ordinance is a dummy equal to 1 if a county had a wind ordinance in that year.

C.2 Robustness check results for markup analysis

Table C3: Effect of integration of 1 GWh of wind energy on fossil fuel generator markups (\$/MWh)

| | Dependent variable: Hourly markups (\$/MWh) | | |
|----------------------------|---|-------------------|-------------------|
| | (1) | (2) | (3) |
| Wind Generation (GWh) | | | |
| × 1{hour = 0} | −1.875 (0.087)*** | −1.594 (0.071)*** | −1.487 (0.068)*** |
| × 1{hour = 1} | −2.211 (0.096)*** | −1.831 (0.080)*** | −1.139 (0.055)*** |
| × 1{hour = 2} | −2.449 (0.101)*** | −2.022 (0.086)*** | −1.130 (0.061)*** |
| × 1{hour = 3} | −2.532 (0.103)*** | −2.078 (0.089)*** | −1.112 (0.063)*** |
| × 1{hour = 4} | −2.469 (0.106)*** | −2.001 (0.089)*** | −1.063 (0.063)*** |
| × 1{hour = 5} | −2.252 (0.102)*** | −1.767 (0.082)*** | −1.315 (0.071)*** |
| × 1{hour = 6} | −1.363 (0.104)*** | −0.883 (0.085)*** | −3.583 (0.249)*** |
| × 1{hour = 7} | −1.822 (0.093)*** | −1.396 (0.071)*** | −1.309 (0.076)*** |
| × 1{hour = 8} | −1.786 (0.095)*** | −1.389 (0.074)*** | −1.233 (0.095)*** |
| × 1{hour = 9} | −1.546 (0.094)*** | −1.278 (0.079)*** | −1.657 (0.078)*** |
| × 1{hour = 10} | −1.364 (0.098)*** | −1.288 (0.080)*** | −1.640 (0.066)*** |
| × 1{hour = 11} | −1.474 (0.110)*** | −1.519 (0.099)*** | −1.447 (0.069)*** |
| × 1{hour = 12} | −1.340 (0.126)*** | −1.460 (0.122)*** | −1.551 (0.107)*** |
| × 1{hour = 13} | −1.380 (0.119)*** | −1.553 (0.122)*** | −1.799 (0.131)*** |
| × 1{hour = 14} | −1.308 (0.118)*** | −1.655 (0.137)*** | −2.452 (0.222)*** |
| × 1{hour = 15} | −0.932 (0.107)*** | −1.380 (0.123)*** | −3.329 (0.297)*** |
| × 1{hour = 16} | 0.018 (0.144) | −0.374 (0.125)*** | −8.639 (0.882)*** |
| × 1{hour = 17} | −0.527 (0.101)*** | −1.117 (0.132)*** | −3.571 (0.244)*** |
| × 1{hour = 18} | −0.605 (0.102)*** | −1.383 (0.134)*** | −2.621 (0.146)*** |
| × 1{hour = 19} | −1.206 (0.099)*** | −1.781 (0.113)*** | −1.631 (0.063)*** |
| × 1{hour = 20} | −1.157 (0.093)*** | −1.607 (0.098)*** | −1.620 (0.063)*** |
| × 1{hour = 21} | −1.284 (0.099)*** | −1.721 (0.103)*** | −1.110 (0.079)*** |
| × 1{hour = 22} | −1.375 (0.089)*** | −1.519 (0.084)*** | −1.576 (0.074)*** |
| × 1{hour = 23} | −1.668 (0.090)*** | −1.579 (0.079)*** | −1.500 (0.069)*** |
| Generator FE | ✓ | ✓ | ✓ |
| Load and Load ² | | ✓ | ✓ |
| Hour × Month × Year FE | | | ✓ |
| Number of FE | 284 | 284 | 1244 |
| Observations | 619,864 | 619,864 | 619,864 |
| R ² | 0.141 | 0.152 | 0.253 |

This table reports the coefficient estimates of Equation 14. The dependent variable is the markup (\$/MWh) set by the marginal generator i at hour t . The coefficient of interest are the interaction of hourly wind generation (GWh) and indicator of the hour. All regressions use hourly data from August 2011 to December 2014. Standard Errors clustered by generator reported in parenthesis. Significance: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

Table C4: Effect of CREZ completion on hourly wind generation (GWh)

| | Dependent variable: Hourly Wind Generation (GWh) | | |
|---|--|------------------|------------------|
| | (1) | (2) | (3) |
| <i>crez</i> | | | |
| $\times \mathbb{1}\{\text{hour} = 0\}$ | 1.722 (0.206)*** | 0.170 (0.024)*** | 0.228 (0.027)*** |
| $\times \mathbb{1}\{\text{hour} = 1\}$ | 1.706 (0.207)*** | 0.165 (0.024)*** | 0.221 (0.027)*** |
| $\times \mathbb{1}\{\text{hour} = 2\}$ | 1.621 (0.208)*** | 0.160 (0.025)*** | 0.213 (0.028)*** |
| $\times \mathbb{1}\{\text{hour} = 3\}$ | 1.489 (0.207)*** | 0.156 (0.024)*** | 0.202 (0.028)*** |
| $\times \mathbb{1}\{\text{hour} = 4\}$ | 1.336 (0.209)*** | 0.166 (0.023)*** | 0.200 (0.025)*** |
| $\times \mathbb{1}\{\text{hour} = 5\}$ | 1.163 (0.208)*** | 0.171 (0.022)*** | 0.171 (0.021)*** |
| $\times \mathbb{1}\{\text{hour} = 6\}$ | 0.992 (0.207)*** | 0.169 (0.021)*** | 0.147 (0.020)*** |
| $\times \mathbb{1}\{\text{hour} = 7\}$ | 0.827 (0.207)*** | 0.169 (0.020)*** | 0.142 (0.020)*** |
| $\times \mathbb{1}\{\text{hour} = 8\}$ | 0.505 (0.210)*** | 0.161 (0.019)*** | 0.126 (0.018)*** |
| $\times \mathbb{1}\{\text{hour} = 9\}$ | 0.286 (0.213)** | 0.151 (0.018)*** | 0.127 (0.018)*** |
| $\times \mathbb{1}\{\text{hour} = 10\}$ | 0.216 (0.215)* | 0.146 (0.018)*** | 0.128 (0.019)*** |
| $\times \mathbb{1}\{\text{hour} = 11\}$ | 0.047 (0.214) | 0.138 (0.018)*** | 0.123 (0.018)*** |
| $\times \mathbb{1}\{\text{hour} = 12\}$ | -0.113 (0.211) | 0.130 (0.017)*** | 0.115 (0.018)*** |
| $\times \mathbb{1}\{\text{hour} = 13\}$ | -0.193 (0.207) | 0.127 (0.017)*** | 0.107 (0.017)*** |
| $\times \mathbb{1}\{\text{hour} = 14\}$ | -0.147 (0.203) | 0.129 (0.017)*** | 0.106 (0.017)*** |
| $\times \mathbb{1}\{\text{hour} = 15\}$ | -0.059 (0.200) | 0.131 (0.017)*** | 0.102 (0.016)*** |
| $\times \mathbb{1}\{\text{hour} = 16\}$ | 0.038 (0.200) | 0.134 (0.017)*** | 0.102 (0.016)*** |
| $\times \mathbb{1}\{\text{hour} = 17\}$ | 0.105 (0.201) | 0.138 (0.018)*** | 0.099 (0.015)*** |
| $\times \mathbb{1}\{\text{hour} = 18\}$ | 0.313 (0.206)** | 0.149 (0.018)*** | 0.104 (0.016)*** |
| $\times \mathbb{1}\{\text{hour} = 19\}$ | 0.597 (0.205)*** | 0.160 (0.019)*** | 0.124 (0.018)*** |
| $\times \mathbb{1}\{\text{hour} = 20\}$ | 0.844 (0.198)*** | 0.168 (0.020)*** | 0.145 (0.020)*** |
| $\times \mathbb{1}\{\text{hour} = 21\}$ | 1.177 (0.196)*** | 0.179 (0.021)*** | 0.179 (0.023)*** |
| $\times \mathbb{1}\{\text{hour} = 22\}$ | 1.513 (0.199)*** | 0.188 (0.023)*** | 0.207 (0.025)*** |
| $\times \mathbb{1}\{\text{hour} = 23\}$ | 1.676 (0.204)*** | 0.182 (0.023)*** | 0.224 (0.026)*** |
| High System Limit | | ✓ | ✓ |
| Hour \times Month FE | | | ✓ |
| Observations | 29,205 | 29,205 | 29,205 |
| R ² | 0.051 | 0.992 | 0.992 |

This table reports the coefficient estimates of Equation 15. The dependent variable is total wind generation (GWh) at hour t . The coefficient of interest are the interaction of CREZ progress (*crez*) and indicator of the hour. All regressions use hourly data from August 2011 to December 2014. Newey-West Autocorrelation corrected standard errors with a 7 day lag structures reported in parenthesis. Significance: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

C.3 Robustness check results for OLS and IV regressions

Table C5: Effect of CREZ expansion on total wind capacity (MW) - IV results

| | Dependent variable: Total Nameplate Capacity (MW) | | | |
|-----------------------|---|-----------------------|------------------------|----------------------|
| | (1) | (2) | (3) | (4) |
| CREZ | 51.429*** (10.293) | 43.041*** (10.051) | 124.817*** (26.919) | 62.181** (26.786) |
| Time Trend | ✓ | ✓ | ✓ | ✓ |
| Zone FE | ✓ | ✓ | ✓ | ✓ |
| Wind Controls | | ✓ | | ✓ |
| Project Cost Controls | | ✓ | | ✓ |
| Regulatory Controls | | ✓ | | ✓ |
| Demographic Controls | | ✓ | | ✓ |
| Regression | OLS | OLS | 2SLS | 2SLS |
| First Stage F-Stat | | | 15.838 | 12.842 |
| Mean Dep. Variable | 32.939 | 32.939 | 32.939 | 32.939 |
| Observations | 2,032 | 2,024 | 2,032 | 2,024 |
| R ² | 0.137 | 0.218 | 0.088 | 0.216 |

Notes: Columns (1) and (2) show OLS estimation results for Equation 18 and Columns (3) and (4) show 2SLS estimation results for Equation IV2. The dependent variable is total nameplate capacity (MW) of wind projects in a county in year t . The independent variable is a binary variable indicating whether a county is CREZ or not. The IV for 2SLS regressions is whether a county was designated as one of the five RE Zones in 2007. Sample is a balanced panel of all Texas counties from 2012-2019. Time Trend is a cubic polynomial of linear time trend variable, Wind Controls include power curve, capacity factor, and cubic polynomial of wind speed (m/s). Project Cost Controls include average wind project cost, real land price, and median land acreage. Regulatory Controls include FE for PTC and wind ordinance in a county. Demographic controls include average farm size (acres) in 2007, median household income in 2007, and average population over 2007 to 2010. Robust Standard Errors reported in parenthesis. Significance: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

Table C6: Effect of CREZ expansion on total turbines in a county - IV results

| | Dependent variable: Total Turbines in a County | | | |
|-----------------------|--|----------------------|-----------------------|----------------------|
| | (1) | (2) | (3) | (4) |
| CREZ | 27.550*** (5.313) | 23.358*** (5.149) | 59.022*** (13.382) | 30.285** (13.596) |
| Time Trend | ✓ | ✓ | ✓ | ✓ |
| Zone FE | ✓ | ✓ | ✓ | ✓ |
| Wind Controls | | ✓ | | ✓ |
| Project Cost Controls | | ✓ | | ✓ |
| Regulatory Controls | | ✓ | | ✓ |
| Demographic Controls | | ✓ | | ✓ |
| Regression | OLS | OLS | 2SLS | 2SLS |
| First Stage F-Stat | | | 15.838 | 12.842 |
| Mean Dep. Variable | 15.866 | 15.866 | 15.866 | 15.866 |
| Observations | 2,032 | 2,024 | 2,032 | 2,024 |
| R ² | 0.136 | 0.206 | 0.098 | 0.205 |

Notes: Columns (1) and (2) show OLS estimation results for Equation 18 and Columns (3) and (4) show 2SLS estimation results for Equation IV2. The dependent variable is the total wind turbines in a county in year t . The independent variable is a binary variable indicating whether a county is CREZ or not. The IV for 2SLS regressions is whether a county was designated as one of the five RE Zones in 2007. Sample is a balanced panel of all Texas counties from 2012-2019. Time Trend is a cubic polynomial of linear time trend variable, Wind Controls include power curve, capacity factor, and cubic polynomial of wind speed (m/s). Project Cost Controls include average wind project cost, real land price, and median land acreage. Regulatory Controls include FE for PTC and wind ordinance in a county. Demographic controls include average farm size (acres) in 2007, median household income in 2007, and average population over 2007 to 2010. Robust Standard Errors reported in parenthesis. Significance: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

Table C7: Effect of CREZ expansion on average capacity of a wind project - IV results

| | Dependent variable: Average project capacity (MW) | | | |
|-----------------------|---|---------------------|-----------------------|--------------------|
| | (1) | (2) | (3) | (4) |
| CREZ | 16.252*** (4.368) | 10.620** (4.745) | 43.684*** (14.172) | 14.089 (16.136) |
| Time Trend | ✓ | ✓ | ✓ | ✓ |
| Zone FE | ✓ | ✓ | ✓ | ✓ |
| Wind Controls | | ✓ | | ✓ |
| Project Cost Controls | | ✓ | | ✓ |
| Regulatory Controls | | ✓ | | ✓ |
| Demographic Controls | | ✓ | | ✓ |
| Regression | OLS | OLS | 2SLS | 2SLS |
| First Stage F-Stat | | | 15.838 | 12.842 |
| Mean Dep. Variable | 19.911 | 19.911 | 19.911 | 19.911 |
| Observations | 2,032 | 2,024 | 2,032 | 2,024 |
| R ² | 0.122 | 0.196 | 0.097 | 0.195 |

Notes: Columns (1) and (2) show OLS estimation results for Equation 18 and Columns (3) and (4) show 2SLS estimation results for Equation IV2. The dependent variable is the total wind turbines in a county in year t . The independent variable is a binary variable indicating whether a county is CREZ or not. The IV for 2SLS regressions is whether a county was designated as one of the five RE Zones in 2007. Sample is a balanced panel of all Texas counties from 2012-2019. Time Trend is a cubic polynomial of linear time trend variable, Wind Controls include power curve, capacity factor, and cubic polynomial of wind speed (m/s). Project Cost Controls include average wind project cost, real land price, and median land acreage. Regulatory Controls include FE for PTC and wind ordinance in a county. Demographic controls include average farm size (acres) in 2007, median household income in 2007, and average population over 2007 to 2010. Robust Standard Errors reported in parenthesis. Significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

C.4 Robustness check results for matching regressions

Table C8: Effect of CREZ on total wind capacity (MW)

| | Dependent variable: Total Nameplate Capacity (MW) | | | |
|-----------------------|---|----------------------|-----------------------|-----------------------|
| | (1) | (2) | (3) | (4) |
| CREZ | 43.041* (22.676) | 60.425** (27.899) | 71.670*** (26.194) | 72.640*** (26.499) |
| Time Trend | ✓ | ✓ | ✓ | ✓ |
| Wind Controls | ✓ | ✓ | ✓ | ✓ |
| Project Cost Controls | ✓ | ✓ | ✓ | ✓ |
| Regulatory Controls | ✓ | ✓ | ✓ | ✓ |
| Demographic Controls | ✓ | ✓ | ✓ | ✓ |
| FE | Zone | Group | Group | Group × Trend |
| Sample | OLS | Matched | Matched | Matched |
| CEM Weights | | | ✓ | ✓ |
| Mean Dep. Variable | 33.069 | 35.907 | 35.907 | 35.907 |
| Observations | 2,024 | 344 | 344 | 344 |
| R ² | 0.218 | 0.339 | 0.390 | 0.467 |

Notes: The dependent variable is total turbines in a county in year t . The independent variable is a binary variable indicating whether a county is CREZ or not. OLS Sample is a balanced panel of 253 Texas counties from 2012-2019. Matched Sample is a balanced panel of 13 treated (CREZ) and 30 control (non-CREZ) counties from 2012-2019 obtained using CEM. Time Trend is a cubic polynomial of linear time trend variable, Wind Controls include power curve, capacity factor, and cubic polynomial of wind speed. Project Cost Controls include average wind project cost, real land price, and median land acreage. Regulatory Controls include FE for PTC and wind ordinance in a county. Demographic controls include average farm size (acres) in 2007, median household income in 2007, and average population over 2007 to 2010. Robust Standard Errors clustered at the county level reported in parenthesis. Significance: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

Table C9: Effect of CREZ on Total Turbines in a County

| | Dependent variable: Total Turbines in a County | | | |
|-----------------------|--|----------------------|----------------------|-----------------------|
| | (1) | (2) | (3) | (4) |
| CREZ | 23.358** (11.855) | 34.451** (15.718) | 39.826** (15.467) | 39.419*** (13.075) |
| Time Trend | ✓ | ✓ | ✓ | ✓ |
| Wind Controls | ✓ | ✓ | ✓ | ✓ |
| Project Cost Controls | ✓ | ✓ | ✓ | ✓ |
| Regulatory Controls | ✓ | ✓ | ✓ | ✓ |
| Demographic Controls | ✓ | ✓ | ✓ | ✓ |
| FE | Zone | Group | Group | Group × Trend |
| Sample | OLS | Matched | Matched | Matched |
| CEM Weights | | | ✓ | ✓ |
| Mean Dep. Variable | 15.928 | 16.067 | 16.067 | 16.067 |
| Observations | 2,024 | 344 | 344 | 344 |
| R ² | 0.206 | 0.347 | 0.408 | 0.476 |

Notes: The dependent variable is total turbines in a county in year t . The independent variable is a binary variable indicating whether a county is CREZ or not. OLS Sample is a balanced panel of 253 Texas counties from 2012-2019. Matched Sample is a balanced panel of 13 treated (CREZ) and 30 control (non-CREZ) counties from 2012-2019 obtained using CEM. Time Trend is a cubic polynomial of linear time trend variable, Wind Controls include power curve, capacity factor, and cubic polynomial of wind speed. Project Cost Controls include average wind project cost, real land price, and median land acreage. Regulatory Controls include FE for PTC and wind ordinance in a county. Demographic controls include average farm size (acres) in 2007, median household income in 2007, and average population over 2007 to 2010. Robust Standard Errors clustered at the county level reported in parenthesis. Significance: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$

Table C10: Effect of CREZ on Average Capacity (MW) of a wind project in a County

| | Dependent variable: Average Capacity (MW) of a project | | | |
|-----------------------|--|--------------------|---------------------|---------------------|
| | (1) | (2) | (3) | (4) |
| CREZ | 10.620* (10.721) | 26.500 (19.046) | 32.722* (18.832) | 32.756* (19.093) |
| Time Trend | ✓ | ✓ | ✓ | ✓ |
| Wind Controls | ✓ | ✓ | ✓ | ✓ |
| Project Cost Controls | ✓ | ✓ | ✓ | ✓ |
| Regulatory Controls | ✓ | ✓ | ✓ | ✓ |
| Demographic Controls | ✓ | ✓ | ✓ | ✓ |
| FE | Zone | Group | Group | Group × Trend |
| Sample | OLS | Matched | Matched | Matched |
| CEM Weights | | | ✓ | ✓ |
| Mean Dep. Variable | 19.99 | 26.951 | 26.951 | 26.951 |
| Observations | 2,024 | 344 | 344 | 344 |
| R ² | 0.196 | 0.313 | 0.345 | 0.426 |

Notes: The dependent variable is the average capacity of a wind project in a county in year t . The independent variable is a binary variable indicating whether a county is CREZ or not. OLS Sample is a balanced panel of 253 Texas counties from 2012-2019. Matched Sample is a balanced panel of 13 treated (CREZ) and 30 control (non-CREZ) counties from 2012-2019 obtained using CEM. Time Trend is a cubic polynomial of linear time trend variable, Wind Controls include power curve, capacity factor, and cubic polynomial of wind speed. Project Cost Controls include average wind project cost, real land price, and median land acreage. Regulatory Controls include FE for PTC and wind ordinance in a county. Demographic controls include average farm size (acres) in 2007, median household income in 2007, and average population over 2007 to 2010. Robust Standard Errors clustered at the county level reported in parenthesis. Significance: *** $p < 0.01$; ** $p < 0.05$; * $p < 0.1$