

Article

Market Impacts of a Transmission Investment: Evidence from the ERCOT Competitive Renewable Energy Zones Project

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Abstract: Texas has experienced a rapid development of wind power over the last 20 years. Since wind power was developed mostly in desolate areas that are remote from urban centers due to its nature conditions, Texas implemented the Competitive Renewable Energy Zones (CREZ) project, the goal of which is to integrate the wind supply regions with the large demand centers. The objectives of this paper are two-fold. The first is to investigate the impact of the CREZ project on market price convergence. Specifically, this paper analyzes the extent that the transmission project affected wholesale price level, variance, and difference between the regions. The second is to measure environmental benefits obtained from displacement of fossil fuel generators by wind power. The results provide a strong evidence for price convergence across the ERCOT market following the completion of the CREZ project. As well as price convergence, wholesale price level and variance are also reduced significantly. Specifically, the results show that the price difference between Houston and West which diverged up to around \$100/MWh converges to zero after the project completed. The impacts are more significant during the high demand hours. The results also document significant reductions in emissions, as NO_x emissions was reduced by around 4000 pounds in Texas as a whole. Effects on SO₂ and CO₂ are also calculated.

Keywords: transmission expansion; wind power; wholesale electricity prices; environmental benefits

1. Introduction

Texas is where wind power has developed rapidly over the last 20 years. In Texas, coal and natural gas accounted for 90% of the total generation in 1990, which was reduced to 75% in 2017. Over the same period, wind power offsetted these decreases, which accounted for 15% of the total generation in 2017 (see Figure 1). These changes can be attributed to rich wind resources, and policy measures including the Renewable Portfolio Standard and the production tax credit for newly installed renewable capacity. Due to its nature conditions, wind power developed mainly in West Texas, the Texas Panhandle and along the Gulf Coast, which are sparsely populated and remote from the urban centers in east and south of Texas, including, for example, Houston, Dallas, and Austin. Currently, about 89% of the wind generation capacity is installed in desolate areas in West Texas and the Texas Panhandle, and the remaining 11% is located by the Gulf Coast ([1]). With the increasing penetration of wind power and growing demand for electricity in urban centers, Texas implemented the Competitive Renewable Energy Zones (CREZ) project, which is a state-level transmission plan to connect the West Texas and other areas with abundant wind power with the large demand centers in the ERCOT market (see Figure 2). ERCOT, the Electric Reliability Council of Texas, is electricity market wholly contained within Texas, covering 75% of Texas land area. ERCOT serves 85% of the state's electric load and has 87% of the state's generation capacity ([2]). The project was completed by the end of January 2014. The expansion of transmission was followed quickly by the construction of new wind capacity, as well

as the wind curtailment dropped from 17% to 1.2%. ERCOT also reported its lowest average wholesale electricity price of \$24.62/MWh in 2016 ([3]).

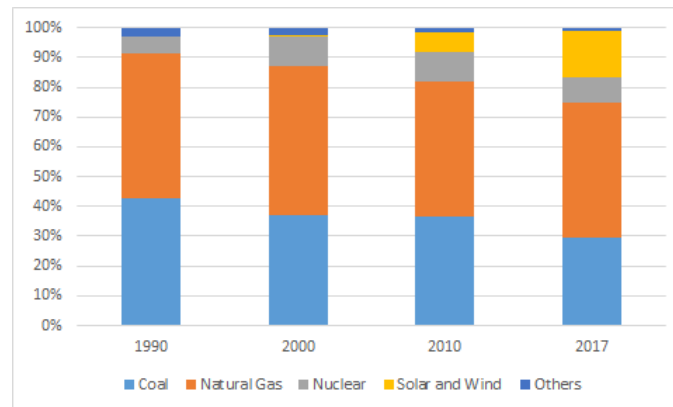


Figure 1. Texas electricity generation mix.

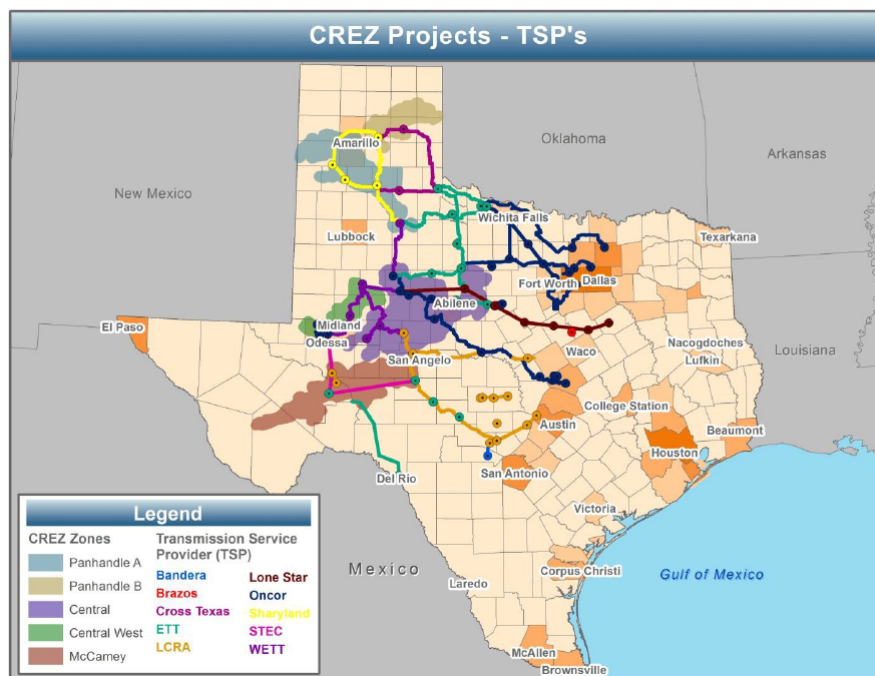


Figure 2. The Competitive Renewable Energy Zones (CREZ) project. Source: [3].

The literature has documented that growing renewable energies introduces a new situation into the market. References [4–6] show that an increase in wind power in electricity generation decreases spot electricity prices, while it is likely to enlarge spot price variance. An increase in wind power displaces marginal generation with high fuel cost which results in lower spot market prices, but it comes at cost of an increase in spot price variance. The variance increases because wind power is characterized as variable renewable energy due to its fluctuating nature, which is not dispatchable other than when nature provides. Reference [7] reports that a marginal increase of 1 GWh of electricity production using renewable energies is associated with a 4% reduction of wholesale electricity prices in Spain. However, the paper also reports that the magnitude of the marginal effects of renewable energies on prices tends to decrease as the contribution of gas power plants increases in the market. The increase in renewable energies is offsetted by the increase in natural gas in Spanish electricity market, where gas power plants set the marginal price at the wholesale market most of the time ([7] discusses that another possible reason could be that firms have market power, which can push prices up to compensate for the impact of renewables. Although this hypothesis is hard to reject, the issue is

to devise a measure for market power that allows us to isolate this effect.). Reference [8] simulates competitive benchmark prices for Summer of 2000 in California, which is the period when wholesale electricity prices were nearly 500% higher than they were during the same months in the previous years. Reference [8] argues that there is a significant gap between the benchmark competitive prices and observed prices, suggesting that the prices observed during the Summer of 2000 in part reflect the exercise of market power by electricity generators. In the context of the liberalization process in UK, Reference [9] argues that reducing the market shares of the incumbent electricity producers through divestment series was more effective to mitigate the volatility of wholesale electricity prices than price-cap regulation. Reference [10] shows that benefits arising from increased solar power mostly correspond to the consumer's side, due to the lower electricity prices. The greatest welfare is generated during the month of January, when both price and quantity are higher.

High levels of variable renewable energies, mainly wind and solar, introduces challenges to delivering reliable and secure electricity supply. Reference [11] highlights that as the increasing share of renewable energy sources increases uncertainties faced by market participants, risk-averse agents can deviate from the centralized planning. Reference [12] investigates the role of the demand-side flexibility, represented by a congested distribution grid and an energy storage system, to mitigate price volatility and price spikes. The rise of variable renewable energies also strengthens the importance of geographic integration and interconnection between regions ([13]). In this paper, we exploit the Texas experience, the CREZ project, to analyze to what extent transmission expansion relieves price volatility and generates environmental benefits. While the CREZ project has not been widely studied in the literature, recently, Reference [1] finds strong evidence for price convergence across ERCOT following the transmission expansion of the CREZ. Moreover, like most of other electricity markets, coal and nuclear dominate base load and natural gas is used for intermediate and peak demand in Texas. As wind power replaces these traditional fossil fuel generators, significant reductions in emissions of pollutants could be expected.

In Economics, there has been a small literature on the transmission networks in electricity markets. Reference [14] analyzes the allocation of transmission rights, which shows that both financial and physical rights can interact with preexisting electricity generators and consumers market power in ways that can enhance market power. Physical rights may potentially have worse welfare effects than financial rights, as physical transmission capacity can be withheld from the market. Reference [15] studies the value of transmission integration in the context of Indian electricity market. Based on Cournot simulations, Reference [15] shows that surplus gains obtained from increases of transmission capacity to integrate the country's electricity market are large, and the benefits are mostly due to strategic firms that increase supply in response to more integrated grid.

While these studies have used theoretical models or simulations rather than econometric analysis, recently, Reference [16] presented a novel econometric approach to estimate the impact of transmission constraints arising from the abrupt closure of the nuclear power plants in California of the United States. The econometric approach enables us to quantify the importance of transmission constraints, but does not require strong assumptions on the firm's objective function or an explicit representation of the transmission networks, which is important because often times such data are not available to the researchers.

The objectives of this paper are two-fold. The first is to explore the impact of the CREZ project on market price convergence. If the CREZ project was effective to integrate wind power and relieve the transmission congestion between the regions, we could expect to observe lower wholesale electricity prices and price convergence between the regions in the market. This paper analyzes to what extent the transmission project affected the wholesale price level, variance, and difference between the regions. The second is to analyze the environmental benefits obtained from displacement of fossil fuel generators by wind power. Specifically, this paper builds on Reference [16] to estimate changes in emissions of pollutants at each generating unit, and calculate how much of this decrease is due to the CREZ project. Our results provide a strong evidence for price convergence across the ERCOT regions

in accordance with the completion of the CREZ project. As well as the price convergence, wholesale price level and variance are also reduced significantly, which are more significant during the high demand hours. However, we should note that part of the price convergence is owing to the fact that we use hourly prices in the day-ahead wholesale markets rather than spot prices, the behavior may be different than that of prices in real-time markets, where the price variance increases responding to increase in wind power generation. The results also document significant environmental benefits obtained from displacement of fossil fuel generators by wind power.

The remainder of paper is organized as follows—in Section 2, we discuss the dataset and present some descriptive statistics. Section 3 presents the model and estimation method. Section 4 provides the empirical results and the last section concludes the paper.

2. Data and Descriptive Statistics

2.1. Data

We first introduce the price data we employ in this study. The price regressions in this paper is based on hourly wholesale electricity prices obtained from ERCOT. Specifically, the paper uses wholesale electricity prices at four locations, that is, West, North, South, and Houston regions in the day-ahead wholesale markets over the period of 1 January 2012 to 31 December 2015 (see Figure 3). Therefore, the data covers two years before and two years after the completion of the CREZ project. While it would be interesting to examine longer-run changes in the market by expanding the data to cover longer period, it gets difficult to identify the impacts because the market is changing over time, both endogenously and exogenously, for example, as new generation sources come into the market in response to the transmission investment. Since we are interested to investigate the impacts of the CREZ project on the market, we restrict our attention to the period when we are able to identify the market changes arising from the the transmission project not from the other factors.



Figure 3. The ERCOT price zones. Source: [17].

To investigate the impact of the CREZ project on unit-level generation and emissions, we also build a database of hourly emissions, heat input, and electricity generation by generating unit from EPA’s Air Markets Program Data from 1 January 2012 to 31 December 2015. All generating units that

are greater than 25 MW are required to report to the Air Markets Program. The constructed dataset consists of 42 coal generators and 332 natural gas generators, or the total of 6,076,690 observations over the sample period. ERCOT has more than 500 generators with diverse fuel types, including natural gas, coal, nuclear, hydroelectric, petroleum, and renewable energies. Despite the incomplete coverage, our data cover the largest fossil fuel generators and the generators that are best able to respond to market conditions, in addition to being the only publicly available hourly data at the generating unit-level.

2.2. Descriptive Statistics

Figure 4 plots average weekly prices for each of the four locations over the sample period, where the vertical line indicates the time the CREZ was completed. Before the project was completed, the prices diverge and the price differences between the regions are significant, especially the West price is more volatile and higher than the prices in other regions. After the CREZ was completed, the prices track each other very closely. Moreover, it seems that the level of wholesale prices tend to reduce in the post-period. Figure 5 plots the difference of weekly average prices between Houston and West, that is, the electricity demand and the wind supply. The graph shows that the price difference was large and volatile during the pre-period, where the price in Houston is lower than that in West for most of the pre-period. The difference converges to around zero following the completion of the CREZ project. Also, Table 1 shows that the correlation coefficients between West and the other regions, that is, West and Houston, West and North, and West and South, increased significantly. For example, the correlation coefficient between West and Houston increased from 0.90 in the pre-period to 0.97 in the post-period. Finally, a simple regression of the hourly price difference between Houston and West on the CREZ dummy that is equal to 1 in the post-period, in Table 2, indicates that on average the hourly price difference is reduced by -2.40 MWh in the post-period.

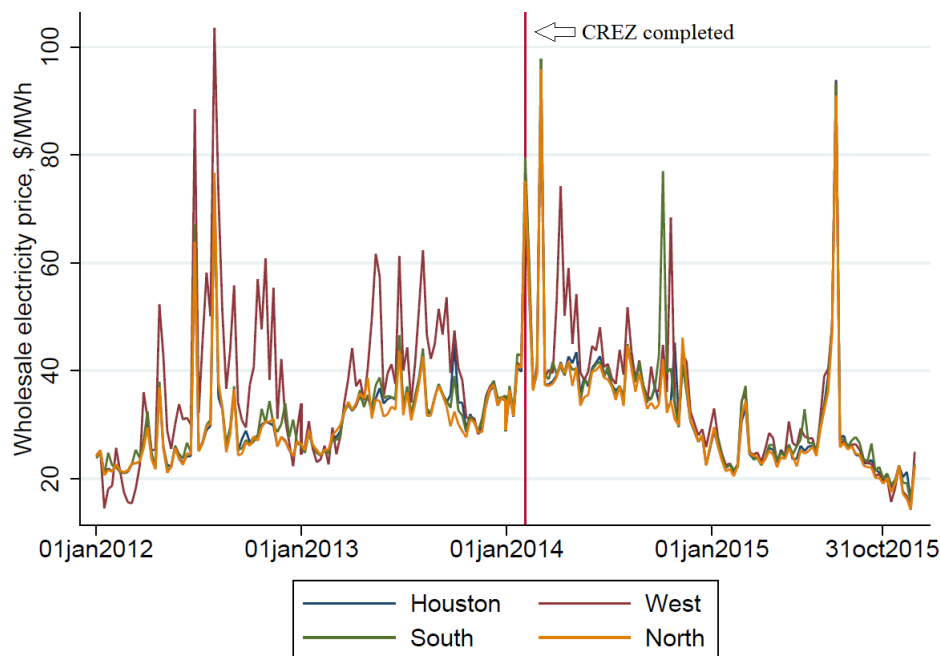


Figure 4. The trend of the ERCOT spot prices. Note: This figure plots average weekly prices for each region in Texas wholesale electricity market over the period of 1 January 2012 to 31 December 2015. The red line where price is more volatile and diverges from those for other regions is for West, and the other three lines are for Houston, South, and North, respectively. The vertical line indicates 30 January 2014, the day the CREZ project was completed.

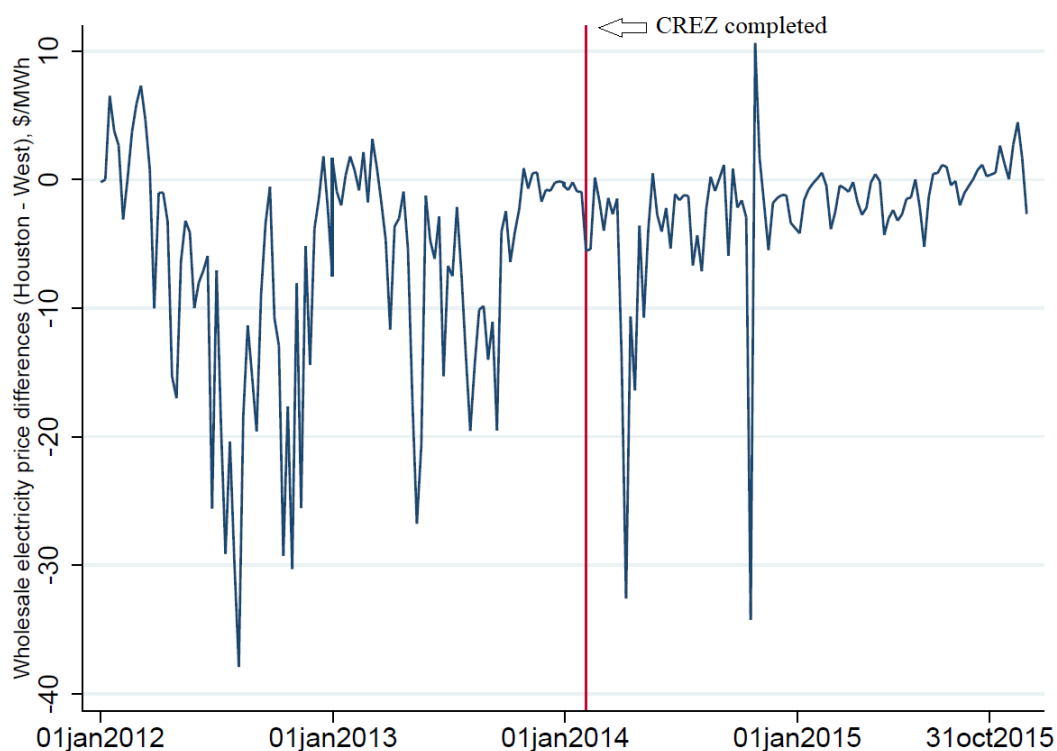


Figure 5. Evidence of decreasing transmission constraints. Note: This figure plots the difference of average weekly prices between Houston and West, i.e., electricity demand and wind supply, respectively, over the period of 1 January 2012 to 31 December 2015. The vertical line indicates 30 January 2014, the day the CREZ project was completed.

Table 1. Correlation coefficients.

	Houston	North	West	South
Before the CREZ Completed				
Houston	1.00			
North	0.99	1.00		
West	0.90	0.90	1.00	
South	0.99	0.99	0.90	1.00
After the CREZ Completed				
Houston	1.00			
North	0.99	1.00		
West	0.97	0.97	1.00	
South	0.97	0.97	0.95	1.00

Table 2. Change in price difference after the CREZ project.

Dependent Variable: Price Difference between Houston and West	
CREZ	−2.40 ** (0.25)
Number of observations	35,056
Adj R ²	0.01

Notes: Standard errors are robust in parentheses clustered at the date. ** Significant at 5 percent or stricter.

Table 3 presents the summary statistics of electricity generation and pollutant emissions including SO₂, NO_x, and CO₂, by generation category over the sample period. Table 3 reports average hourly generation by generating unit, with standard deviations in the parentheses. Comparing the period before and after the CREZ project, coal generation decreased by 32 MWh at the sample mean, which accounts for 6% of the average hourly generation of all coal generators in the data in the pre-period. Partially offsetting these decreases, natural gas generation increased by 8.91 MWh. The decreased coal generation accompanied significant reductions of pollutant emissions, SO₂, NO_x, and CO₂, by 13%, 13%, and 5%, respectively.

Table 4 describes the summary statistics of electricity generation and pollutant emissions by generation category, distinguished by price region. While coal generation decreased in the other regions, including North, South, and West, it is not statistically different in Houston before and after the CREZ project. Coal generation decreased the most in West, which is reduced by 85 MWh. Specifically, an average coal generator produced 508 MWh in the pre-period, while it is reduced to 423 MWh in the post period. Natural gas generation shows the opposite. While natural gas generation increased in North, South, and West in the post-period, it decreased by 7 MWh in Houston. Natural gas generation increased the most in West, by 16 MWh. It suggests that the development of wind power in West mostly affected fossil fuel generators located in the same region, where wind power replaced coal generators while natural gas generators increased its generation in response to the volatility of wind power. The fact that fossil fuel generation decreased in Houston is consistent with that the correlation coefficient between Houston and West increased from 0.90 in the pre-period to 0.97 in the post-period in Table 1, that is, fossil fuel generation in Houston, especially natural gas generation that is more costly than coal generation is replaced by wind power developed in West.

Table 3. Texas electricity generation by generation category, 2012–2015.

	Before	After	Change	
<i>Panel A. Coal</i>				
Load (MWh)	508 (221)	476 (227)	−32 ** (0.40)	−6%
SO ₂ (pounds)	2296 (2304)	1989 (2075)	−307 ** (3.99)	−13%
NO _x (pounds)	668 (796)	575 (403)	−92 ** (1.16)	−13%
CO ₂ (short tons)	531 (227)	504 (229)	−27 ** (0.41)	−5%
<i>Panel B. Natural gas</i>				
Load (MWh)	152 (94)	161 (92)	8.91 ** (0.08)	6%
SO ₂ (pounds)	1.06 (6.78)	1.12 (2.88)	0.05 ** (0.004)	5%
NO _x (pounds)	48 (71)	45 (74)	−3.61 ** (0.06)	8%
CO ₂ (short tons)	78 (41)	82 (40)	3.82 ** (0.03)	5%
Number of observations	3,158,725	2,917,965		
Number of generators				
<i>Coal</i>	42	42		
<i>Natural gas</i>	322	332		

Notes: Standard deviations are in the parentheses. ** Significant at 5 percent or stricter.

Table 4. Texas electricity generation by generation category and region, 2012–2015.

	Coal			Natural Gas		
	Before	After	Change	Before	After	Change
<i>Panel A. Houston</i>						
Load (MWh)	530 (155)	530 (165)	0.30 (0.92)	159 (106)	152 (96)	−7 ** (0.18)
SO ₂ (pounds)	2755 (1503)	2798 (1637)	42 ** (9)	1.44 (2.34)	1.53 (2.75)	0.08 ** (0.004)
NOx (pounds)	258 (94)	268 (101)	10 ** (0.56)	29 (61)	29 (68)	0.32 ** (0.11)
CO ₂ (short tons)	548 (156)	540 (160)	−8 ** (0.91)	81 (39)	85 (41)	4 ** (0.07)
<i>Panel B. North</i>						
Load (MWh)	562 (263)	530 (268)	−31 ** (0.73)	182 (83)	196 (84)	14 ** (0.15)
SO ₂ (pounds)	3077 (2778)	2502 (2483)	−575 ** (7)	0.93 (3.85)	0.94 (1.93)	0.01 ** (0.005)
NOx (pounds)	860 (1087)	717 (424)	−143 ** (2)	43 (38)	40 (39)	−2.52 ** (0.07)
CO ₂ (short tons)	592 (270)	568 (269)	−24 ** (0.74)	87 (35)	91 (35)	4 ** (0.06)
<i>Panel C. South</i>						
Load (MWh)	459 (172)	420 (171)	−38 ** (0.57)	156 (89)	159 (84)	3 ** (0.18)
SO ₂ (pounds)	1369 (1821)	1287 (1736)	−81 ** (5)	0.86 (15.41)	0.82 (3.52)	−0.03 (0.02)
NOx (pounds)	437 (246)	407 (222)	−30 ** (0.78)	48 (73)	40 (63)	−8 ** (0.14)
CO ₂ (short tons)	480 (175)	449 (171)	−31 ** (0.58)	75 (38)	76 (34)	0.87 ** (0.08)
<i>Panel D. West</i>						
Load (MWh)	508 (169)	423 (198)	−85 ** (2)	96 (63)	112 (76)	16 ** (0.22)
SO ₂ (pounds)	996 (401)	729 (491)	−267 ** (5)	0.62 (4.43)	0.69 (4.69)	0.07 ** (0.01)
NOx (pounds)	1724 (772)	1477 (798)	−247 ** (9)	74 (75)	68 (78)	−5 ** (0.24)
CO ₂ (short tons)	543 (177)	456 (207)	−87 ** (2)	58 (28)	57 (30)	−0.33 ** (0.09)
Number of observations	634,353	579,535		2,525,172	2,338,430	
Number of generators						
<i>Houston</i>	4	4		76	75	
<i>North</i>	19	19		72	78	
<i>South</i>	12	12		72	73	
<i>West</i>	1	1		36	40	

Notes: Standard deviations are in the parentheses. ** Significant at 5 percent or stricter.

3. Empirical Model

3.1. Price Regressions

The data show significant price convergence across the regions as well as decrease in the price level following the completion of the CREZ project. The paper now proceeds to analyze how much of these changes is due to the CREZ project. To answer these questions, the paper builds on [16] to

describe this relationship semi-parametrically, using a series of regressions, estimated separately before and after the project for each of the price region. The estimating equation takes the following form:

$$p_{it} = \sum_b (\gamma_{bi} \cdot 1\{\text{system} - \text{wide demand}_t = b\}) + \epsilon_{it}, \quad (1)$$

where p_{it} is the wholesale electricity price for region i in hour t . The independent variables in the regression are a set of indicator variables corresponding to different levels of the total wholesale market demand. We divide the total market demand into bins of equal width, indexed by b , where the bin width is defined as $18,500/10 = 1850$ MWh, given that the CREZ project was designed to accommodate 18,500 MW of wind ([3]). We have experimented with alternative bin widths, and the results are very similar across both more and fewer bins. The equation does not include a constant in the regression, as the indicator variables sum to unity. Without a constant, the coefficients γ_{bi} are equal to the average hourly price for region i when the wholesale market demand is in bin b . The standard errors are robust clustered by the date to allow for arbitrary spatial correlation and serial correlation within the date.

3.2. Generation Regressions

Generation regressions describe the relationship between system-wide demand and generation at individual sources. We first estimate these regressions for categories of generation, coal and natural gas, and then for individual generating units. For the generation regressions by category the estimating equation is written as:

$$Q_{it} = \sum_b (\beta_{bi} \cdot 1\{\text{system} - \text{wide thermal generation}_t = b\}) + e_{it}, \quad (2)$$

where Q_{it} is electricity generation for fuel type i in hour t , measured in megawatt hours. In contrast to price regressions in (1), Equation (2) divide system-wide thermal generation into bins of equal width, indexed by b , instead of system-wide demand, because we now want to identify the ordering of generation category and attribute changes from the pre-period to the post-period to the CREZ project not to market conditions including the demand. As with Equation (1), we do not include a constant in the regression. Therefore, the coefficients β_{bi} are equal to the average generation for fuel category i when system-wide thermal generation is in bin b . The standard errors are clustered by date to allow for arbitrary spatial correlation and serial correlation within date.

The generation regressions by category provide an overview, but no detail which particular generating units tend to be more responsive to changes in market conditions arising from the transmission project. We therefore next estimate generation regressions for each generating unit that appears in the data. The estimating equation is very similar to Equation (2), where fuel type i is replaced with individual generating unit j .

$$Q_{jt} = \sum_b (\alpha_{bj} \cdot 1\{\text{system} - \text{wide thermal generation}_t = b\}) + \mu_{jt}, \quad (3)$$

where Q_{jt} is electricity generation for the unit j in hour t . On the right hand side, we use system-wide thermal generation, that is, the total generation by all the units in our sample, because we want to identify the ordering of the units. In Equation (3), α_{bj} is interpreted as the average hourly generation for unit j when the system-wide thermal generation is in bin b . We cluster the standard errors by date to allow for arbitrary spatial correlation and serial correlation within date.

Since we have data on hourly emissions of pollutants at each generating unit, we are able to quantify the changes in pollutant emissions before and after the CREZ project. We use the same

regression as we used for the generation regressions by individual generating unit, but with pollutant emissions as the dependent variable.

$$E_{jt} = \sum_b \left(\lambda_{bj} \cdot 1\{\text{system-wide thermal generation}_t = b\} \right) + v_{jt}, \quad (4)$$

where E_{jt} is the pollutant emissions for the unit j in hour t , measured by SO_2 , NO_x , and CO_2 . Therefore, the coefficients λ_{bj} are equal to the average emissions of pollutants for generating unit j when system-wide thermal generation is in bin b . The standard errors are again clustered by date to allow for arbitrary spatial correlation and serial correlation within date.

3.3. Predicted and Residual Effects

From the estimation of Equations (3) and (4), we have a set of coefficients α and λ for each of bin b at more than 300 individual generating units, separately for pre- and post-period. We use these coefficient estimates to calculate predicted and residual effects. We distinguish between the two effects. Predicted effects measure change in generation associated with the next generating units along the marginal cost curve being brought into the system. Residual effects measure change in generation associated with a change in the order of the generating units along the supply curve. While the predicted effects measure a non-marginal shift arising from the transmission project in the net demand faced by individual generating unit given that the order of marginal costs did not change, the residual effects measure differences between actual and predicted generation, reflecting transmission constraints and other physical limitations of the grid as well as noncompetitive behavior.

For each generating unit, predicted effects are calculated by maintaining the coefficients from the pre-period, 18,500 MWh of generation, that is, $b = 10$ bins, are filled by wind.

$$\sum_{b>n} \sum_{j \in J} \left(\alpha_{b-n,j}^{pre} - \alpha_{bj}^{pre} \right) \cdot \theta_{b-n}^{post}, \quad (5)$$

where $n = 10$ we set the bin width at 1850 MW. θ_{b-n}^{post} is the fraction of hours that the system-wide demand was in bin $b - n$ during the post-period. Equation (5) models the predicted effects how a unit's behavior changes when the net demand it faces changes, given that the order of marginal costs did not change by maintaining the coefficients from the pre-period.

We measure the residual effects by calculating the change in generation from the pre-period to post-period, conditional on a given level of the system demand.

$$\sum_{b>n} \sum_{j \in J} \left(\alpha_{b-n,j}^{post} - \alpha_{b-n,j}^{pre} \right) \cdot \theta_{b-n}^{post}. \quad (6)$$

The residual effect measures how the unit's behavior changes before and after the CREZ project given level of the system demand. Residual effects can be positive or negative, reflecting whether units are operating more or less than would be predicted from pre-period behavior.

4. Results

We estimate Equation (1) separately before and after the CREZ project, using the hourly data from 1 January 2012 to 29 January 2014, and from 30 January 2014 to 31 December 2015, respectively. Because the coefficients γ_{bi} are allowed to differ by the region, we estimate the total of 8 separate equations, one for each region for each of the pre- and post-period. Figure 6 presents the coefficient estimates. In Figure 6, the x -axis is the total wholesale market demand divided into bins, and the y -axis is the coefficient estimates, which represent the average hourly prices in MWh for each region when the system demand is in bin b . The results show that compared with the prices in the pre-period, the prices in the post-period are lower and less volatile, especially during the high demand hours.

For example, the average hourly price in Houston increases from \$58.94 to \$111.98 as the demand bin increases from 23 to 24, and to \$248.96 as the bin increases to 26 in the pre-period. The corresponding average hourly price in Houston in the post-period reduces to \$54.18, \$66.53, and \$200.19, respectively. The level of wholesale market demand corresponding to the bin 23, 24, and 26 are 61,052 MWh to 62,890 MWh, 62,906 MWh to 64,746 MWh, and 66,627 MWh to 68,317 MWh, respectively. The results are similar across the regions.

While the literature has documented that the development of wind power increases the variance of electricity prices, this paper finds the opposite results. It has two reasons. First, we use hourly price data in the day-ahead wholesale markets rather than spot markets. The behavior of the day-ahead prices would be different than that of prices in spot markets, where the price volatility increases in response to increases in wind power. Second, the reduced price volatility in Figure 6 can be partly interpreted as the impacts that the CREZ project brought into the market, as the project relieves the transmission congestion.

Figure 7 presents the coefficient estimates of the price difference between Houston and West by demand quantile. This is obtained by replacing the dependent variable in Equation (1) with Δp_t , where Δp_t denotes the price difference between Houston and West. While the price difference significantly enlarges during the high demand hours in the pre-period, the price difference converges to around zero in the post-period.

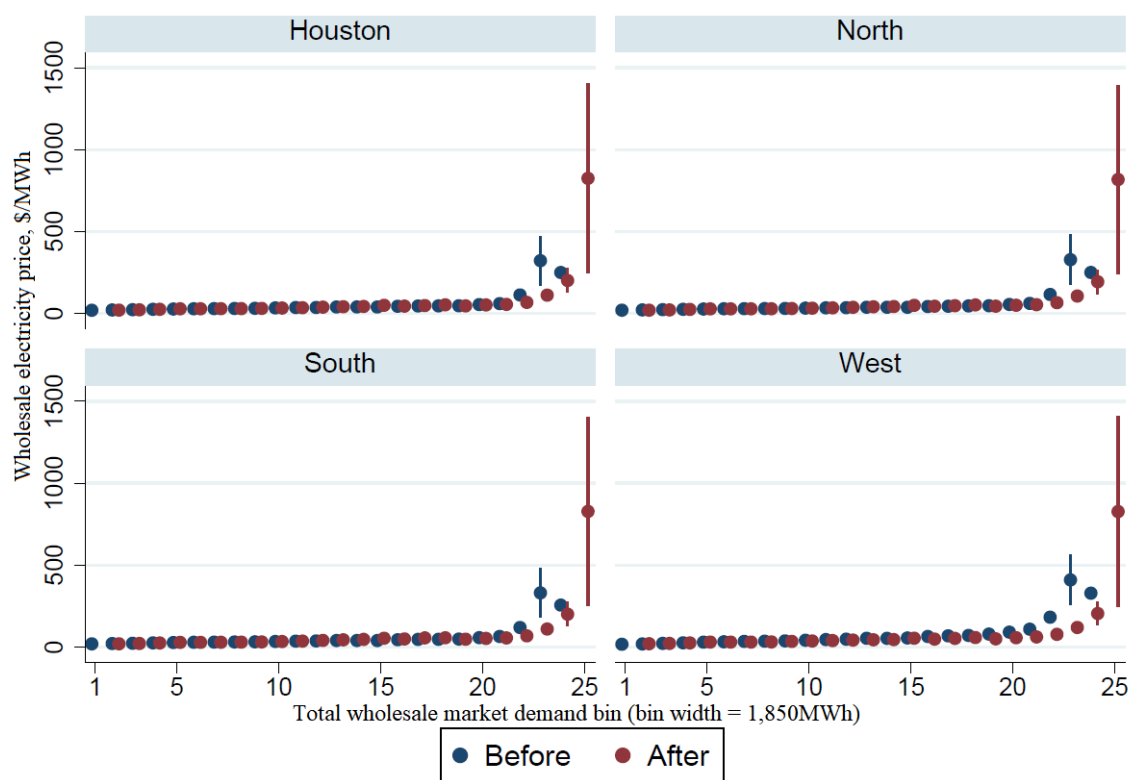


Figure 6. Price regression coefficients by demand quantile.

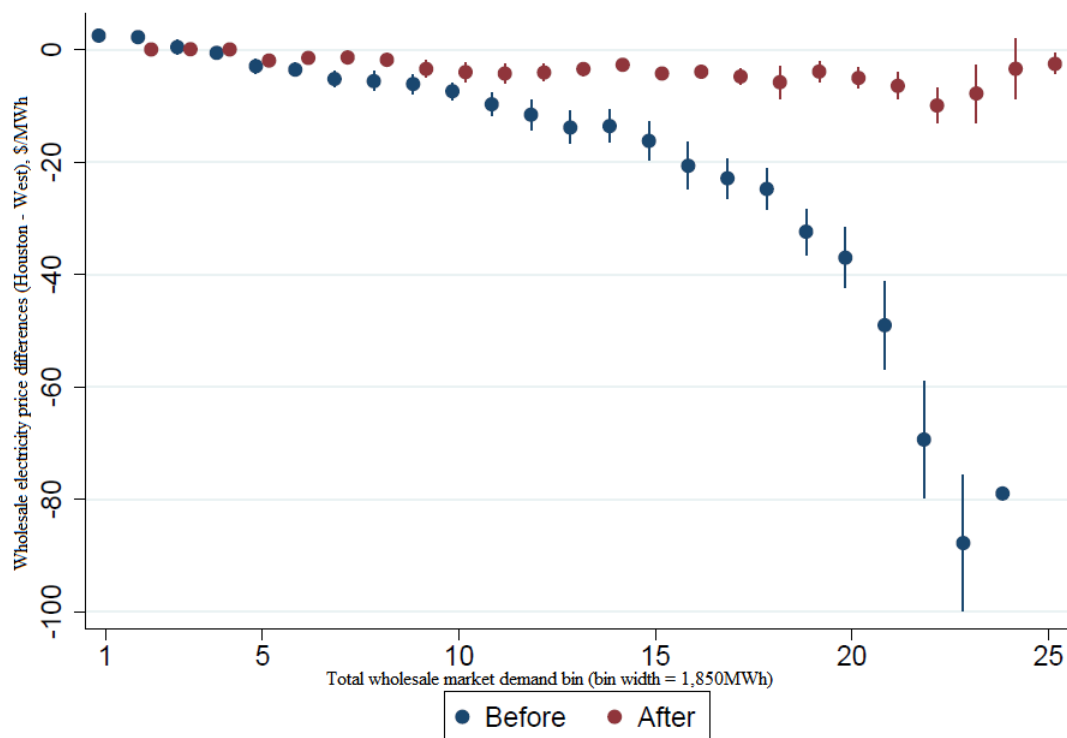


Figure 7. Regression coefficients of price difference by demand quantile.

Figure 8 plots the coefficient estimates of Equation (2). In Figure 8, the x -axis is the system-wide thermal generation from all units in the data, and the y -axis is the average fuel specific generation in MWh. Comparing coal and natural gas generation, natural gas generation is more responsive across all level of the demand, for both pre- and post-period. Moreover, Figure 8 shows that coal and natural gas generation are differently affected by the CREZ project. While coal generation decreased in the post-period, especially for lower level of the demand, natural gas generation increased in the post-period. It suggests that the accommodation of wind power from the CREZ project mostly replaced coal generation, while natural gas generation, which is more flexible than coal generation, increased in response to the volatility of wind power. This is consistent with the summary statistics in Table 3. In part, the increased natural gas generation could be driven by the coincidence of decreased natural gas prices during the sample period. We have estimated alternative models including different sets of fixed effects, where the fixed effects could control for demand- and supply-side effects that vary by time of day or by season, which provide very similar results across the specifications.

We estimate the unit-level regressions in Equation (3) for individual generating unit for each of the pre- and post-period. Figure 9 shows six sample graphs of the coefficients. The three graphs on the top panel show coal generators, while the other three graphs on the bottom panel show natural gas generators. The x -axis is total generation from all fossil fuel units in the data, and y -axis is average generation in MWh for that individual unit. While we found that coal generation decreased and natural gas generation increased in the market as a whole during the post-period in Figure 8, Figure 9 emphasizes that the impacts are heterogeneous across the individual generators. For example, the first two graphs on the top panel show that coal generation decreased in the post-period, while the third graph shows the impacts are insignificant. Similarly, the first graph on the bottom panel shows increased natural gas generation. However, the second graph on the bottom panel presents an example where natural gas generation decreased in the post-period, although the magnitude is small. The third natural gas generator shows almost no impacts.

Moreover, the results suggest that the impact of the transmission project on the behavior of individual generators may vary hour to hour. For example, while both of the first two coal graphs

decreased generation in the post-period, the first unit shows that the decrease is more significant during the high demand period. In contrast, the second graph shows the increased generation during the high demand period. It implies that although the the transmission project shifted the entire distribution of net demand, the ability of individual generating units to respond to changes in demand is different hour to hour as well as across generation categories.

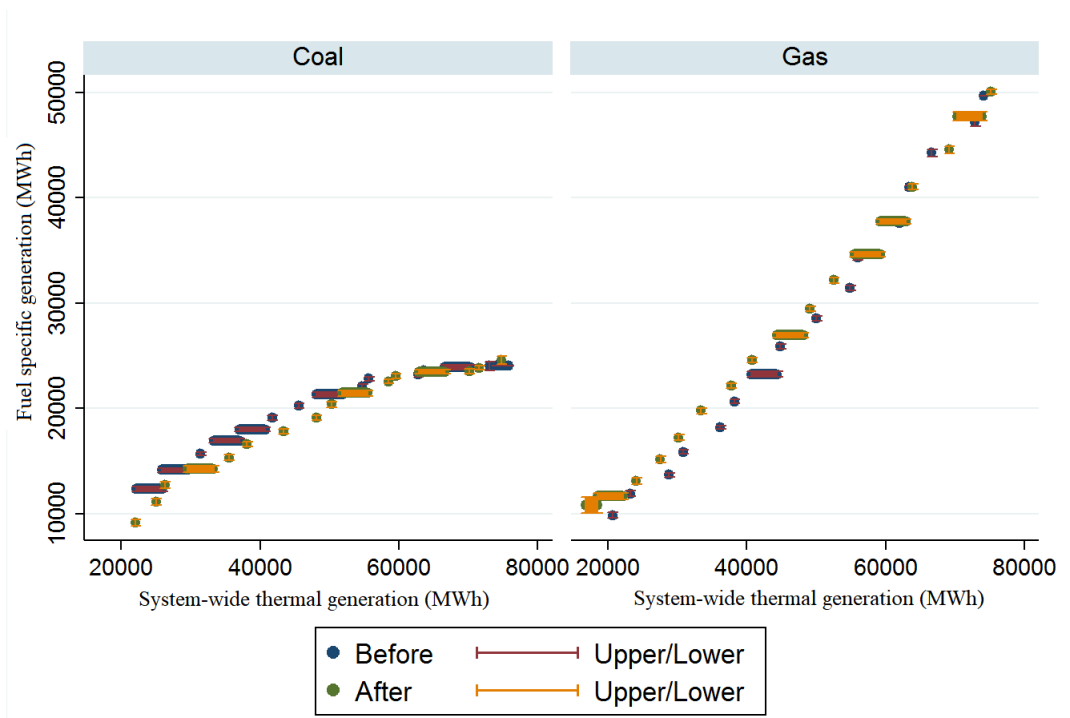


Figure 8. Generation regressions by category.

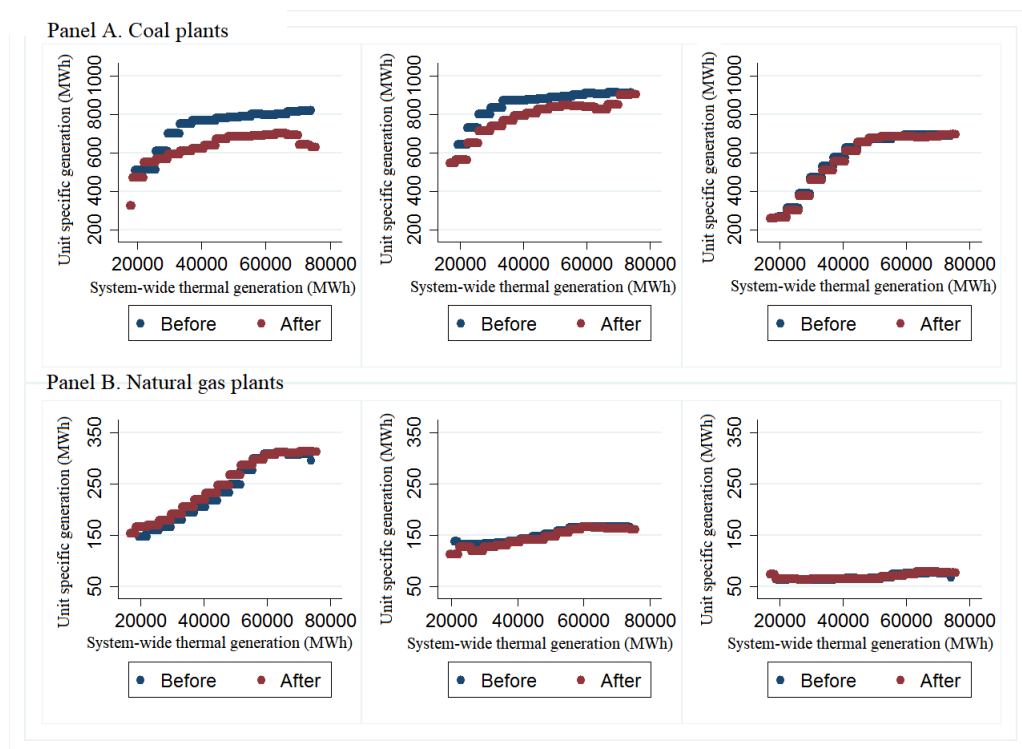


Figure 9. Unit-level regressions.

Finally, Table 5 describes the predicted and residual effects of the CREZ project on the geographic pattern of generation and pollutant emissions in Texas. Table 5 demonstrates significant reductions in fossil fuel generation and pollutant emissions in all regions. While the predicted effects are negative in all regions, for both electricity generation and emissions of pollutants, the impacts are largest in Houston which has high demand for electricity from urban centers. Interestingly, the residual effects for electricity generation is positive in West, which may arise from the increased natural gas generation responding to the accommodation of wind power. Or, as we discussed earlier, the increased natural gas generation could be in part driven by the decreased natural gas prices during the sample period. Another explanation could be that the transmission project created incentives for investments in remote areas in West Texas. This is supported by the fact in Table 4, where the number of natural gas generators increased from 36 in the pre-period to 40 in the post-period. Houston exhibits the positive residual effects for SO₂ and CO₂. The residual effects for SO₂ is also positive in North. These two regions are where a large number of coal generators locate corresponding to high electricity demand from populated areas (see Figures 2 and 3). Although the residual effects for electricity generation is positive due to the increased natural gas generation in West, the residual effects for pollutant emissions are negative in this region. It is because natural gas plants emit small enough amount of these pollutants compared with coal plants.

Table 5. Predicted and residual effects.

	Houston	North	South	West	Total
Effects on generation					
Predicted effects	−1747	−838	−584	−98	−3267
Residual effects	−5	−116	−238	83	−276
Effects on NO _x					
Predicted effects	−1944	−616	−495	−285	−3340
Residual effects	−94	−273	−133	−162	−662
Effects on SO ₂					
Predicted effects	−1851	−970	−175	−21	−3017
Residual effects	242	20	−486	−60	−284
Effects on CO ₂					
Predicted effects	−1165	−559	−385	−117	−2226
Residual effects	42	−84	−136	−67	−245

Overall, our results provide a strong evidence for price convergence and integration of Texas wholesale electricity market following the CREZ project. Moreover, as the integration of wind power replaced mostly coal generation, the project had a large environmental impact, by decreasing significant amount of pollutant emissions. The impacts are greatest in Houston, where populated urban centers introduce high demand for electricity. However, Houston also locates a significant number of coal generators corresponding to high electricity demand, yielding relatively less environmental benefits from integrated wind power.

5. Conclusions

The intermittent nature of renewable resources introduces a variety of challenges to the system, including, for example, variability, location specificity, and transmission congestion. Due to its nature conditions in Texas, wind power has rapidly developed in West Texas, the Texas Panhandle and along the Gulf Coast, which are sparsely populated and remote from the urban centers in east and south of Texas. This introduced a significant wind curtailment and price divergence across the ERCOT market. With the increasing development of wind power and growing demand for electricity in urban areas, Texas implemented the Competitive Renewable Energy Zones (CREZ) project, which is a state-level

transmission plan to connect the areas with abundant wind power with the large demand centers in Texas.

This paper utilizes the CREZ experience to investigate the impact of transmission investment on the market prices as well as the environmental benefits obtained from displacement of fossil fuel generators by wind power. Specifically, this paper builds on Reference [16] to analyze the extent that the transmission project affected the wholesale price level, variance, and difference between the regions. This paper also estimates changes in emissions of pollutants at each fossil fuel generator, and calculate how much of this decrease is due to the transmission project. The results provide a strong evidence for price convergence across the wholesale market following the completion of the CREZ project. The wholesale price level and variance are also reduced significantly in all price regions, where the impacts are more significant during the high demand hours. The results also document significant environmental benefits from displacement of fossil fuel generators.

Although our approach enables us to quantify the impact of transmission expansion based on publicly available data while not requiring strong structural assumptions, our model sharply distinguishes the period before and after the CREZ project, which means that the effect is identified given that the transmission investment is an exogenous event to the market. However, since firms would make generation decisions in response to the plans of transmission expansion, the effect is eventually an endogenous outcome. Ultimately, a formal model that describes firm's decisions taking into the transmission expansion plans account will be needed to identify the effect.

Finally, transmission investment may have an another important impact on the market. Transmission congestion increases the possibility for noncompetitive behavior for certain plants, especially during high-demand periods. Therefore, existing market power can introduce the cost of greater complexity and monitoring into the market, as firms have incentives to exercise market power to compensate for the impact of renewables. This suggests that quantifying the welfare effects resulting from transmission investment should include the benefits of competition to consumers, which will be addressed in our future research.

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