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Emissions, Transmission, and the Environmental Value of Renewable Energy

Harrison Fell* and Daniel T. Kaffine† and Kevin Novan‡

Abstract

We examine how transmission congestion alters the environmental benefits provided by renewable generation. Using hourly data from the Texas and Mid-Continent electricity markets, we find that relaxing transmission constraints between the wind-rich areas and the demand centers of the respective markets conservatively increases the non-market value of wind by 31% for Texas and 13% for Mid-Continent markets. Much of this increase in the non-market value arises from a redistribution in where air quality improvements occur – when transmission is not constrained, wind offsets much more pollution from fossil fuel units located near highly populated demand centers.

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1 Introduction

Across the U.S., large utilities spent roughly $21 billion on electricity transmission infrastructure in 2016 alone, with billions more planned for future years (see FERC Form 1). Much of this infrastructure has been and will continue to be built to deliver power from sparsely populated regions rich in renewable energy (wind and solar) to more populated regions where demand for electricity is much higher. Regional price differences driven by grid congestion give rise to obvious arbitrage opportunities. However, grid congestion (or the alleviation thereof through transmission expansion) may not only affect the private value of renewable energy, but also its social or environmental value. Specifically, congestion can impact the *level* and *location* of emissions avoided by renewable generation. In other words, transmission lines carry both the electrons as well as the improvements to local air quality that are produced by renewable energy.

In this paper, theoretical and empirical analyses are used to examine how grid congestion affects the environmental benefits of wind generation, explicitly accounting for spatially-specific damages from local pollutants as well as damages from global pollutants. Our findings reveal that grid congestion can significantly reduce the environmental value of renewables. In particular, insufficient transmission capacity can prevent renewable generation produced in less-populated regions from reducing dirty fossil generation and thus local emissions in high-damage populated areas, illustrating that the *location* channel is critical in assessing the environmental value of renewable energy.

Our analysis employs several key features. First, we utilize county-specific damage estimates for local pollutants, allowing us to capture substantial heterogeneity in environmental damages associated with emissions from fossil plants. Second, our theoretical and empirical approaches allow us to examine how transmission and congestion affect the non-market value of wind generation, as well as how wind generation affects the non-market value of transmission. Third, we leverage rich hourly data to exploit significant variation in load conditions, wind generation, and grid congestion. Using market data to identify the existence of congestion raises some endogeneity concerns, so we employ recently developed machine learning techniques to generate parsimonious instrumental variables from a set of more than 1,500 plausibly exogenous instruments. Finally, we use our parameter estimates to assess the non-market value of a transmission expansion project completed in early 2014 in Texas.

With a simple two-region theoretical model, we show that relaxing a transmission constraint between regions affects the environmental value of renewables through two channels: offsetting different conventional generators can affect the *level* of emission reductions due to differences in emission rates, and it can also alter the *location* of where those emissions are offset. For local pollutants, this *location* channel is particularly important, as emissions near heavily populated demand centers can impose very large external damages, potentially orders of magnitude larger than in sparsely populated but renewable-rich regions (Muller and Mendelsohn (2009), Zivin et al. (2014), Holland et al. (2016), Jha and Muller (2017)).

Our empirical application, conducted separately for the Texas electricity market (ERCOT) and the market that encompasses much of the mid-continent portion of the U.S. (MISO), finds a consistent reduction of local and global emissions damages due to wind generation. Importantly, environmental damages offset by wind generation are lower, at statistically and economically significant levels, during periods of transmission congestion. For example, wind in ERCOT offsets $53 dollars per MWh in uncongested periods, compared to only \$40 dollars per MWh in congested periods. In terms of mechanisms for this disparity, we find the marginal value of wind in terms of local pollutant reductions falls considerably during congested hours (the marginal value is lowered by 35 percent in ERCOT and 14 percent in MISO), but reductions in CO_2 damages are much less affected by congestion (marginal values are reduced by 8 and 7 percents, respectively, across ERCOT and MISO). Our estimates are robust to a battery of alternative assumptions and specifications, and our interpretation is well-supported by an array of analyses into the underlying mechanisms.

These findings have important consequences on several fronts. First, the serious health consequences of local air pollution have been well-documented (Currie and Walker 2011; Schlenker and Walker 2016; Deschênes et al. 2017; Deryugina et al. 2018), and this paper highlights the role that transmission networks can play in moving air quality improvements from renewable-rich to renewable-poor areas. Second, while low and even negative market prices due to transmission congestion have received substantial attention, by robustly quantifying how transmission congestion reduces the environmental value of wind generation, our results show that the environmental consequences of grid congestion can also be quite serious.[1] This is particularly important for renewable generators as they have been heavily subsidized in large part on the grounds that they provide certain environmental benefits, and our results suggest that if this support for renewables is not also met with transmission infrastructure support, much of the perceived environmental value may be lost. Third, given the large sums of money being spent on transmission upgrades, our findings and analysis frame-

[1] The occurrence of negative energy prices due to grid congestion in renewable-rich regions like California and Texas has garnered a great deal of comment in the popular press. For example, see a recent Bloomberg article, "One Thing California, Texas Have in Common is Negative Power," `https://www.bloomberg.com/news/articles/2016-04-05/one-thing-california-texas-have-in-common-is-negative-power`.

work more generally are important in evaluating non-market values of these investments.[2] Indeed, we use our parameter estimates to calculate a back-of-the envelope environmental value of a $7 billion transmission project undertaken in ERCOT – the Competitive Renewable Energy Zone (CREZ) upgrades which increased the transmission capacity between the wind-rich west portion of the market to the demand-rich east. Our results indicate that the reduced grid congestion brought about by the CREZ project increased the environmental value of ERCOT's wind generation by $450 million dollars annually, with three-quarters of this value coming from decreased local-pollutant damages.

Our findings contribute to multiple strands of literature. Similar to the trade and the environment literature (Copeland and Taylor (1994), Copeland and Taylor (1995), Antweiler et al. (2001), Davis and Kahn (2010), Cherniwchan (2017)), we also assess how barriers to trade (in this case through transmission constraints) impact environmental outcomes, finding that transmission-related barriers to electricity trade are, on average, environmentally harmful. Our work is also related to the environmental economics literature on non-uniformly mixed pollutants and/or pollutants with location specific damages (e.g. Muller and Mendelsohn (2009), Holland and Yates (2015), Fowlie and Muller (2017)). Despite the fact that support of renewable power has become one of the major environmental policies worldwide, this literature has not examined the indirect regulation of emissions with spatially heteroge-

[2] As noted here, `https://www.eia.gov/todayinenergy/detail.php?id=348922`, expansion of the transmission system to integrate renewables (and natural gas) is noted as one of the primary factors driving transmission investment. Examples include MISO approval of the $6.6 billion Multi-Value Portfolio transmission project to provide greater access to the region's wind generation, as well as the $13 billion spent by California utilities on transmission expansions from 2003 through 2012, much of which went towards connecting Southern California demand centers to renewable-rich regions to the east (`https://www.eia.gov/todayinenergy/detail.php?id=17811`). A private firm, Clean Line Energy Partners, also has four planned projects totalling nearly $9 billion dollars to explicitly move wind energy from the plains to demand centers in the eastern US and southern California (see `https://www.cleanlineenergy.com/projects`).

neous damages through the support of renewable energy.

More directly related, there have been several studies assessing the environmental value of renewable energy (e.g. Callaway et al. (2018), Fell and Kaffine (2018), Cullen (2013), Kaffine et al. (2013), Novan (2015)). In contrast to these studies, we explicitly account for county-specific damages, and thus our estimates of the environmental value of wind generation are driven by both the type and location of avoided emissions. Two related econometric applications examine how the CREZ project affected curtailment rates (Dorsey-Palmateer 2017) and private welfare measures (LaRiviere and Lu 2017). However these studies do not account for how grid congestion alters the spatial pattern of location-specific emission damage reductions from wind generation. To our knowledge, this is the first econometric study that assesses the role that transmission constraints play in determining the non-market value of renewables.[3] As we show, this turns out to be quite important as congestion alters the levels and spatial pattern of pollution damages avoided by renewables.

2 Conceptual Framework

This section provides intuition as to how increases in transmission capacity can affect the non-market value of renewable generation. To do so, we extend the transmission models in Joskow and Tirole (2005) and LaRiviere and Lu (2017) to include renewables and a negative externality in the form of unpriced emissions. Using the model, we highlight how the envi-

[3] Note that Davis and Hausman (2016) use an econometric approach in analyzing the market and non-market impacts arising from transmission constraints due to a nuclear plant closure. There have also been several simulation-based studies that have more explicitly considered the location of renewable generation siting and/or the use of transmission expansion to increase the value of renewables (e.g Drechsler et al. (2011), Neuhoff et al. (2013), Schill et al. (2015), Hitaj (2015), Drechsler et al. (2017)). These studies necessitate many assumptions about possible generator responses and often use less-detailed transmission network assumptions. To our knowledge this literature, much of which comes from engineering disciplines, also fails to account for spatially heterogenous emission damages.

ronmental damage avoided by additional renewable generation can vary across uncongested (i.e. transmission unconstrained) and congested (i.e. transmission constrained) periods.

Consider two regions, West and East, where West represents a renewable-rich region that produces W units of renewable electricity from (for example) wind turbines at zero marginal cost. Let $MC_w(F_w)$ represent the marginal cost of fossil generation F_w in the West, and similarly $MC_e(F_e)$ in the East. Electricity demand (load) in the West and East, L_w and L_e, respectively, is assumed to be fixed. The regions can also trade power, Q, such that $|Q| \leq K$, where K is the transmission constraint, so $F_w = L_w - W + Q$ and $F_e = L_e - Q$.[4] Therefore, assuming perfectly competitive generators, when the system is uncongested ($Q < K$):

$$MC_w(L_w - W + Q) = MC_e(L_e - Q). \tag{1}$$

This implies that an exogenous, marginal increase in wind will alter the trade between regions and fossil generation in each region according to the relative slopes of the regional marginal cost curves: $\frac{dQ}{dW} = \frac{MC'_w}{MC'_e + MC'_w}$; $\frac{dF_w}{dW} = -\frac{MC'_e}{MC'_e + MC'_w}$; and $\frac{dF_e}{dW} = -\frac{MC'_w}{MC'_e + MC'_w}$.

When the system is congested ($Q = K$), regional prices and marginal costs will differ:

$$MC_e(L_e - Q^c) = MC_w(L_w - W + Q^c) + \eta(K), \tag{2}$$

where $\eta(K) > 0$ is the shadow cost of the transmission constraint. The resulting marginal effects of wind generation are now $\frac{dQ^c}{dW} = 0$, $\frac{dF^c_e}{dW} = 0$, and $\frac{dF^c_w}{dW} = -1$. With a binding transmission constraint, additional wind generation is fully absorbed by West fossil generators.

Consider now emissions associated with fossil generation in the above model, where we distinguish between global pollutants (CO_2) and local pollutants (e.g., SO_2, NO_x, PM2.5).

[4] We are implicitly assuming that L_w and L_e are sufficiently large to accommodate some fossil generation in both regions. This assumption appears appropriate for our empirical setting as only about 3.75% of sample observations have zero fossil fuel generation in the wind-rich west region of ERCOT. For MISO, we observe fossil generation in the wind-rich zones, as well as all other zones, in all hours of our sample.

Global pollution from each region is given by $g_i(F_i) > 0$ for $i = \{w, e\}$, and similarly for local pollutants $s_i(F_i) > 0$, where $g'_i > 0$ and $s'_i > 0$. Let γ_g represent the (common) dollar damages per unit of global pollutant, while δ_w and δ_e represent damages from local pollutants emitted in the West and East. Total environmental damages can then be expressed as:

$$D(W) = \gamma_g \Big[g_w\big(F_w(W)\big) + g_e\big(F_e(W)\big) \Big] + \delta_w s_w\big(F_w(W)\big) + \delta_e s_e\big(F_e(W)\big). \qquad (3)$$

We can now compare the marginal environmental damages across uncongested and congested periods. Differentiating with respect to W yields the following expression for how wind affects environmental damages in an uncongested market:

$$\frac{dD}{dW} = -\gamma_g \left(g'_w \frac{MC'_e}{MC'_e + MC'_w} + g'_e \frac{MC'_w}{MC'_e + MC'_w} \right) - \delta_w s'_w \frac{MC'_e}{MC'_e + MC'_w} - \delta_e s'_e \frac{MC'_w}{MC'_e + MC'_w}, \qquad (4)$$

which expresses the change in environmental damages in terms of the marginal emission rates in each region – i.e. g'_i and s'_i evaluated at the equilibrium level of fossil generation in each region – and the marginal damages per unit of pollution, γ_g and δ_i. Conversely, differentiating Equation 3 with respect to W when the system is congested yields the following:

$$\frac{dD^c}{dW} = -\gamma_g g'_w(F^c_w) - \delta_w s'_w(F^c_w). \qquad (5)$$

While inspection of Equations 4 and 5 reveals the important distinction that wind in congested markets will only offset West fossil generation, whereas wind in uncongested markets offsets fossil generation anywhere, direct comparison is complicated by the fact that the West emissions functions are evaluated at different levels of generation (F_w vs. F^c_w). If we make the (strong) assumption that marginal emission rates are the same (locally), $g'_w(F_w) = g'_w(F^c_w)$ and $s'_w(F_w) = s'_w(F^c_w)$, and simplify the notation such that $\delta_e = \delta(1 + \nu)$ and $\delta_w = \delta$, then the difference in damages offset by wind in uncongested versus congested markets is:

$$\frac{dD}{dW} - \frac{dD^c}{dW} = \underbrace{\Big[\gamma_g(g'_w - g'_e) + \delta(s'_w - s'_e)\Big]\frac{MC'_w}{MC'_e + MC'_w}}_{\text{Emissions Level Effect}} - \underbrace{\delta\nu s'_e \frac{MC'_w}{MC'_e + MC'_w}}_{\text{Emissions Location Effect}} . \tag{6}$$

The *Emissions Level Effect* reflects the change in damages arising from the fact that marginal emission rates may be different across the two regions, and thus, the level of emissions avoided from wind may change. The *Emissions Location Effect* reflects the fact that increased exports due to wind in the West will reduce local pollution in the East, which may have different marginal damages. Ultimately, the *Level Effect* has an ambiguous impact on how congestion affects the environmental value of wind. In contrast, if local marginal damages are higher in the East ($\nu > 0$), the *Location Effect* unambiguously increases the environmental value of wind during uncongested periods relative to congested periods.[5]

Applying the above insights to our empirical setting, we expect that when transmission is constrained, an increase in wind will tend to offset generation near wind facilities primarily located in renewable-rich regions which are often sparsely populated. In contrast, when transmission is unconstrained (i.e. the market is uncongested), an increase in wind may offset generation in distant, often more heavily populated regions. This pattern suggests that, when markets are uncongested, the *Emissions Location Effect* increases the environmental value of wind as more local pollution is offset near the populated demand centers – precisely where local pollutants impose the largest damages.

[5] If we relax the assumption that marginal emission rates are locally similar, such that $g'_w(F^c_w) = g'_w(F_w) + \alpha_g$ and $s'_w(F^c_w) = s'_w(F_w) + \alpha_s$, then a third term emerges in Equation 6: $\gamma_g\alpha_g + \delta_w\alpha_w$. This *Supply-curve effect* captures movement along the fossil supply curve due to congestion constraints, reflecting the emissions rate of the particular fossil generator offset by wind. In practice, the emissions functions g_i and s_i may be globally non-linear with non-monotonic first derivatives, so the sign of this effect is theoretically ambiguous. While this effect is embedded in our empirical estimates below, we focus more on the *Level* and *Location* effects due to the theoretical ambiguity and difficulty of empirically isolating this *Supply-curve effect.*

3 Data and methods

Our empirical analysis begins with a thorough investigation of ERCOT, with description of data sources and methodologies described below. To demonstrate that our findings are more broadly applicable, we then apply a similar analysis to the MISO region in Section 5. These two market regions have the highest wind generation of all the ISO/RTO regions in the U.S. and much of the wind generation is concentrated in the less-populated portions of their market footprints (see Figure 1), similar to the US more generally and several other nations.[6] Based on plant-specific monthly generation in the EIA-923 data, over our sample the sparsely populated West Zone in ERCOT accounts for 70-85% of ERCOT's total wind generation and, similarly, wind generation from the less densely populated western states in MISO (IA, MN, MT, ND, and SD) account for 75-90% of MISO's wind generation.

3.1 Data

In this section, we discuss the market, generation, and weather data collected for ERCOT in detail.[7] Our analysis uses hourly observations from 2011-2015. We begin by creating measures of the hourly environmental damages from all electricity generators in ERCOT across the four load zones (West, North, South, and Houston). From the EPA's Air Markets Program Data (AMPD) database, we collect hourly generation and emission data from each generating unit.[8] In addition, using EIA 860 data, we identify the county in which each

[6] As a non-U.S. example of this siting issue, consider China, which is currently investing more in renewable energy than any other nation. China has strong wind and solar generation potential in its more remote north and west regions, far from its eastern population centers. As a result of this siting and lack of transmission, a high percentage of this renewable generation is curtailed (see https://www.vox.com/2016/3/30/11332900/china-long-distance-transmission).

[7] The data for our analysis of MISO is similarly structured and will be discussed briefly in section 5.

[8] While the AMPD database is the root source of the data, we accessed this data via ABB's Velocity Suite data tool which combines publicly available data on power plants, along with some variables that

generating unit is located. We then pair this emissions and location data with the county-specific marginal damages associated with emissions of SO_2, NO_X, and PM2.5 as reported in Holland et al. (2016).[9] Taking all this together, the ERCOT-wide environmental damages during any given hour h can be calculated as:

$$D_h = \sum_i \sum_p s_{pc} \cdot f_{ipch}, \tag{7}$$

where f_{ipch} represents the hourly emissions of pollutant p from plant i in county c during hour h and s_{pc} is the dollar damages per unit of pollutant p emitted in county c. While s_{pc} is constant across counties for CO_2, s_{pc} varies substantially across counties for SO_2, NO_X, and PM2.5.[10] Additional analyses disaggregate ERCOT-wide damages into load zone-specific damages as well as global damages (CO_2) and local damages (SO_2, NO_X, and PM2.5).

To highlight why the environmental value of wind generation may depend on the spatial pattern of offset conventional output, we first explore how the marginal damage from fossil fuel generators varies across the four zones of the ERCOT market. To do so, we regress the hourly damages in a given zone on the aggregate hourly fossil fuel generation in the corresponding zone, allowing the marginal damage estimate to vary freely by the hour of day. For each zonal regression we use the full sample of data (2011 through 2015) and we

result from ABB's own analysis, into a single searchable database. Additionally, we restrict the sample to generating units listed in the EIA-defined sectors of "non-cogen electric utility" or "non-cogen independent power producers" as these are the sectors likely to be participating in the ERCOT electricity market.

[9] Note, the AMPD data does not report PM2.5 emissions and thus we impute these values. To do this, we take the annual county-specific PM2.5 emission readings for the electricity sectors for the years 2008, 2011, 2014 as reported in the EPA's National Emissions Inventory. We regress these emissions on annual county-specific levels of generation from coal- and gas-fired power plants as reported through the AMPD database, along with year fixed effects. The parameters on coal and gas generation then serve as our emission coefficients for generators of those respective types. One concern here might be that, for coal plants particularly, their may be certain emission control technologies that vary by plant and thus a common emissions factor is inappropriate. However, in ERCOT all coal plants in our sample have the same emissions control equipment with regards to PM2.5 and thus this is likely not an issue.

[10] For CO_2 damages, we use the constant marginal value of \$39/tCO_2 based on the U.S. interagency working group's case of a 3% average discount rate for year 2015. All damages are given in 2011 dollars.

include hour-by-month-by-year fixed effects to flexibly control for factors that could create a spurious correlation between the hourly fossil generation and damages. Figure 4 displays the average marginal damage estimates for each zone and for each hour of day. Marginal damages per MWh are substantially higher in all hours in Houston, particularly in off-peak hours when coal is more likely the marginal fuel source. By contrast, fossil fuel generation in the West is cleaner, implying that environmental benefits of wind in ERCOT are expected to be higher when that wind can offset generation in Houston instead of in the West.

Ultimately, to explore how the non-market value of wind varies with market conditions, we regress hourly environmental damages on hourly ERCOT wind generation, measures of market congestion, and importantly, a large set of controls. To control for shifts in electricity demand, we include hourly load (electricity consumed) at the the ERCOT-wide level and at the load-zone level.[11] To control for changes in the merit order of generation units, we include natural gas-to-coal price ratios. For coal prices, we use the ABB Velocity Suite estimated plant-level coal cost, and form capacity weighted average prices by load zone. For the natural gas price, ABB assigns a gas hub, a point where gas prices are quoted, to each plant based on their location. We then assign a gas price to each plant based on the plant's ABB-assigned gas hub price. We again form load-zone-wide gas prices as capacity weighted averages of these plant-specific prices. The gas-to-coal price ratio is the ratio of these average prices. Table 1 provides summary statistics for the hourly damages from emissions, zonal prices, and the other key explanatory variables used in our analysis.

We use several approaches to classify whether the market is congested during a given

[11] We treat electricity demand as completely inelastic and exogenous. At the hourly frequency, this is a plausible assumption and one commonly made in the literature.

hour. ERCOT reports 15 minute real-time market prices for each zone (which themselves are averages across prices at multiple resource nodes) that we then average at the hour by zone. Given ERCOT's pricing structure, a difference in zonal prices implies the presence of congestion. Examination of the data suggests that there are hours where the ERCOT market is clearly uncongested (single price across zones) and hours where the ERCOT market is clearly congested (very different prices across zones).[12]

A more challenging classification issue is when there are differences in zonal prices that are "small." Our base specification begins by calculating the simple average of the six pairwise differences in hourly electricity prices across the four ERCOT load zones (West, North, South, Houston). This average hourly price spread, which we define as $Spread_{hdmy}$, can be thought of as a measure of the average (unreported) congestion price in ERCOT for that hour. We then create an indicator variable C_{hdmy} for congestion which takes the value of 1 when the average price spread exceeds some cutoff value c. Formally,

$$C_{hdmy} = 1(Spread_{hdmy} > c), \tag{8}$$

where c is set to \$1 in our base specification. We also examine different cutoff values (c), construct alternative congestion indicators based on specific pairwise price comparisons or multiple indicators based on multiple pairwise price comparisons, and drop observations when differences in zonal price are greater than zero but small (i.e. drop a "donut" to compare between clearly uncongested and clearly congested hours). These alternative strategies yield results that are qualitatively, and often quantitatively, similar to the main results.

Using our base specification described above, we find the ERCOT market was congested

[12] For example, when prices in all zones are \$23.17, the market is clearly uncongested. Similarly, when ERCOT West price is \$10 and ERCOT North, South and West prices are \$45, congestion is clearly preventing power from moving out of ERCOT West.

38% of the hours from 2011 through 2015. Figure 3, which displays the average number of congested hours across each month of the sample, highlights that there is considerable variation in the frequency of congested hours. Consistent with the CREZ transmission expansions reducing the occurrence of congested hours, Figure 3 displays a substantial drop-off in congested hours during 2014 and 2015 – the post-CREZ expansion years (based on ERCOT documentation, the bulk of CREZ is completed around mid-to-late 2013 – see Appendix A).[13] As a robustness check, we ultimately utilize the CREZ transmission expansions as an instrumental variable for congestion, which we describe in more detail below.

3.2 Empirical strategy

Our base regression specification takes the following form:

$$D_{hdmy} = \beta_1 W_{hdmy} + \beta_2 W_{hdmy} C_{hdmy} + \beta_3 C_{hdmy} + \sum_i \theta_i^j f_i(X_{hdmy}) + \gamma_{hm} + \eta_{my} + \delta_d + \epsilon_{hdmy}, \quad (9)$$

where D_{hdmy} is ERCOT-wide environmental damages for hour h, day d, month m and year y. Our two variables of interest are W_{hdmy}, which is hourly ERCOT wind generation in MWh, and C_{hdmy}, which is an indicator for whether the market was congested. X_{hdmy} is a set of controls for load and the fuel price ratio between gas and coal, which typically enter as a quadratic. The remaining fixed effects control for other sources of variation in our outcome variables that may be correlated with our explanatory variables of interest. Hour-by-month fixed effects γ_{hm} control for changes in wind patterns over the course of the day that may be correlated with changes in the shape or composition of the load profile. Month-by-year fixed effects η_{my} control for longer-run trends such as increasing wind capacity and changes in the

[13] Variation in the average price spread over time (demeaned by hour-by-month fixed effects) is also shown in the appendix as Figure B.2.

generation mix (e.g., retirements). We employ day-of-week fixed effects δ_d to capture within-week variation in the load and generation profile. Finally, to account for serial correlation, standard errors are clustered at the month-year level.

Our key coefficients of interest are β_1, representing the marginal effect of wind generation on environmental damages when markets are uncongested, and β_2, representing the change in the marginal effect of wind generation when markets are congested. The expected sign on β_1 is negative – wind should displace fossil fuel, reducing environmental damages, while the expected sign on β_2 is ambiguous per the above discussion in Section 2.

One concern with estimating Equation 9 is that the parameters may be biased if $Congested$ is endogenous. As a robustness check, we apply instrumental variable approaches to address the potential endogeneity. To find suitable instruments for congestion, we first turn to the engineering literature regarding the capacity of electricity transmission lines. While transmission lines are given static capacity ratings, which often reflect a best-case scenario for the amount of power that can flow across the lines, ambient weather conditions such as wind speed and direction, air temperature, and solar radiation can affect the capacity of a line in real time (Wang and Pinter 2014). As these ambient conditions affect transmission capacity levels, these will impact congestion rates in ways which, after controlling for electricity demand and other relevant observables, should be otherwise uncorrelated with environmental damages and satisfy the exclusion restriction.[14] We therefore collect hourly data from weather stations across Texas on these variables to use as possible instruments.

[14] In practice, these ambient weather conditions may influence dispersion rates and exposure rates, which may affect real-time pollution damages "on the ground". However, from a technical perspective, because we are applying average damage rates by county, our total damage value is unaffected by these variables and these weather variables satisfy the exclusion restriction. We are assuming these weather variables have at most a second order impact on our damage rate estimates, given the vast differences in population between West Texas and the rest of the state.

We also exploit the timing of CREZ transmission expansions (using variants of the percent volt-miles completed) as an additional instrument. As noted above, the CREZ expansion project increased transmission capacity from West to East Texas. This project was rolled out in phases over the course of our sample period. Again, this expansion should lower congestion rates, but otherwise not affect damages associated with generation.

To form the full set of instruments used in the analysis, we use two different techniques. In our first, simpler technique, we use the simple averages of the wind speed, wind direction, and solar radiation variables across all weather stations in Texas as well as the percent-CREZ-completed variable. In addition, we interact those four instruments with the hourly ERCOT wind generation, the hourly ERCOT load, and the hourly ERCOT wind generation interacted with hourly load. All together, this results in a set of 16 excluded instruments that we use in our first IV specification.

While these average ambient weather variables give us some sense of the general weather conditions across Texas in a given hour, one may expect that the likelihood of congestion is more heavily affected by weather conditions in a subset of locations within in the state. We therefore consider an instrument set where we average the wind speed, wind direction, solar radiation, and temperature from weather stations at the county level. We also interact these county-specific weather conditions with zonal load, wind generation, and total ERCOT load, as well as consider squared terms of the county-level weather variables. In all, this procedure gives us a total of 1,550 possible instruments. To obtain a more informative set of instruments, we use the IV-LASSO procedure as described in Belloni et al. (2012), wherein a LASSO estimator is used in the first stage to determine the set of instruments and standard IV estimation is then conducted given the selected set of instruments.

4 Results

This section first presents the results from our base specification (Equation 9) which estimates the environmental value of wind in uncongested versus congested market conditions. We then present the corresponding IV estimates, which take advantage of variation in weather conditions and the CREZ expansion, to support the findings from the base specification. This is followed by a series of robustness checks and a closer examination of the underlying mechanisms that drive the differences in the environmental value of wind.

4.1 Environmental value of wind

Estimation results of variants on Equation 9 are given in Table 2, with total environmental damages as the dependent variable. The coefficient on $Wind$ corresponds to β_1 and the coefficient on $Wind$ interacted with $Congested$ corresponds to β_2, and these can be readily interpreted as the average dollar change in environmental damages due to a one MWh increase in wind generation in uncongested (β_1) versus congested ($\beta_1 + \beta_2$) hours.

Results across Table 2 consistently find that the environmental value of wind is greater in uncongested hours compared to congested hours. Column (1) is the most parsimonious specification and only includes month-year, hour-month and day of week fixed effects. Coefficient estimates for $Wind$ and $Wind * Congested$ are similar in Column (2), which adds linear and quadratic controls for total ERCOT load and fuel price ratios.[15] Column (3) adds linear and quadratic controls for average Texas temperatures as well as wind generation and

[15] Note the signs on the coefficients of the quadratic controls for load and fuel price ratio are consistent with expectations. Increases in load unsurprisingly increase environmental damages from emissions but at a decreasing rate, reflecting the fact that higher loads correspond to natural gas as the marginal generating unit further up the dispatch curve. Similarly, increasing gas prices (or falling coal prices) make gas less competitive relative to coal, increasing environmental damages as more coal is dispatched relative to gas (and vice versa for falling gas prices, as was typical during this time period (Fell and Kaffine 2018)).

load in the neighboring Southwest Power Pool (SPP) market, with key coefficients essentially unchanged.[16] Column (4) replaces total ERCOT load with linear and quadratic controls for the zonal loads in the four ERCOT zones, while Column (5) fully interacts all controls and fixed effects from Column (4) with *Congested*.

Taking Column (5) as the preferred specification, during uncongested market conditions an additional MWh of ERCOT wind generation offsets around $53 dollars in environmental damages. In contrast, during congested conditions, the environmental value of an additional MWh of wind falls to roughly $40/MWh – a drop of approximately $13/MWh. In other words, wind is 31% more environmentally valuable when markets are uncongested.

Instrumental variable estimates of Equation 9 are displayed in Table 3. Column (1) provides the results from the basic IV procedure using ERCOT-wide average ambient weather conditions as instruments. Column (2) provides the estimates from the IV-LASSO procedure. The basic IV procedure leads to a slightly larger effect of wind on total damages in uncongested states compared to the OLS estimates, but estimates a much larger loss in the environmental value of wind during congested states (parameter on $Wind \cdot Congested$), such that 70% of the environmental value of wind is lost when the system is congested. The IV-LASSO results are closer to OLS, but still estimate a much larger loss in environmental value of wind generation in congested periods of about 44%.

Why are the IV estimates of the parameter on the wind and congestion interaction term larger? There are several possibilities. First, to the extent *Congested* is endogenous, the IV

[16] Temperature may affect damages independent of load through effects on thermal efficiency of plants. Average temperature is based on hourly readings at 36 ASOS stations across Texas from NOAA's uncongested Surface Database `https://www.ncdc.noaa.gov/isd`. While ERCOT has limited ties to surrounding areas, there are some connections with the neighboring SPP. Hourly wind and load data for SPP are available at `https://marketplace.spp.org/groups/operational_data`.

estimates may be correcting this in a way that leads to larger $Wind * Congested$ parameter estimates. Another issue may be that if *Congested* is not truly binary as modeled here, then Angrist and Imbens (1995) show that IV estimates may be biased upward. To further explore this issue, we consider cuts of the data whereby we drop observations where the average price spread is relatively low in an effort to identify more binary congested and uncongested states. We consider four such settings where we drop all observations when the average price spread is between (1) 0.5 and 1.5; (2) 0.1 and 5; (3) 0.01 and 10; and (4) 0.001 and 15. Parameter estimates on the $Wind * Congested$ interaction term from the IV strategies over these four data settings are consistently, and considerably, higher than the OLS parameter estimates (see Appendix Table B.7), providing evidence that the potentially non-binary *Congested* variable is not driving the larger IV parameter estimates.

It is also possible that we are picking up a local average treatment effect (LATE). Specifically, if the instruments explain the variation in congestion in periods prone to a larger loss in the environmental value of wind, we may be picking up that the LATE differs from the overall average effect. Regardless, the OLS estimates appear to conservatively estimate the impact of congestion on the environmental value of wind. We therefore proceed with a variety of robustness checks and investigations of mechanisms using OLS estimation procedures to demonstrate that, even with more conservative estimation approaches, the impacts of congestion on the environmental value of wind are statistically and economically significant.

4.2 Local vs Global Pollutants

To determine if the loss in environmental value during congested hours is driven by local or global pollutants, we estimate our fully-interacted model with damages from local pollutants

(SO_2, NOX and PM2.5) or global pollutants (CO_2) as the dependent variable. The estimates displayed in Columns (1) and (2) of Table 4 reveal the difference in environmental value in congested versus uncongested periods is primarily driven by changes in local pollutant damages. Of the $13/MWh difference in total damages, $11/MWh can be attributed to local damages versus $2/MWh from CO2.

Recall there are two primary channels through which congestion can affect the environmental value of wind – the Emissions Level Effect and the Emissions Location Effect. For example, the small benefit associated with more CO_2 emissions offset during uncongested hours is driven by the Level Effect, indicating that the composition of the generators that respond to wind is different during uncongested periods.

To more closely explore the Level and Location Effects, we next consider cases where we remove the spatial variation in damages from local pollutants. Doing so isolates the Emissions Level Effect, as a unit of emissions has the same environmental damage regardless of where it is emitted. Columns (3) and (4) of Table 4 replace the spatially-explicit damages from local pollutants with the mean or median damages, respectively, across all counties with a fossil generator. Removing the spatial variation leads to an environmental value of wind in uncongested hours that is lower than in Table 2, and the interaction between $Wind$ and *Congested* is also smaller by roughly half. This suggests that, of the $13 dollar increase in environmental value during uncongested hours found in Table 2, roughly half can be attributed to the Emissions Level Effect (*what* is being offset) and half can be attributed to the Emissions Location Effect (*where* it is being offset).[17]

[17] This is consistent with estimates in Appendix Table B.1 where SO_2, NO_x, PM2.5 and CO_2 emissions are the dependent variable. More SO_2, PM2.5 and CO_2 are offset during uncongested hours, which suggests some degree of coal-to-gas switching (in terms of what type of generation is being offset by wind) is occurring. Interestingly, NO_x shows a small and marginally significant increase in emissions offset by wind

We next consider a set of cases where we expect the Emissions Level Effect to be near-zero. Specifically, we examine subsets of the data where the lone coal plant in the West zone is operating near full capacity (capacity factors in excess of 0.80), likely capturing hours in which natural gas units are on the margin in the West. As expected, results in Column (1) of Table 5 show that, in uncongested periods, wind offsets less CO_2 damage than in Table 4, and the interaction effect is negative and insignificant. Column (2) restricts the sample further to observations where prices in ERCOT West and North are greater than $35 per MWh, such that gas is almost certainly marginal in both regions. The interaction effect is now even more negative and marginally significant.[18] Looking at local damages in these same scenarios finds small positive and insignificant interaction effects (Columns (3) and (4)), consistent with gas as the marginal unit, but where the Emissions Location effect may still be positive due to greater population outside ERCOT West. Finally, in Columns (5) and (6), we examine local damages where we zero out the Emissions Location Effect by replacing county-specific damages with the median damages, leading to interaction effects that are very close to zero. In sum, Table 5 A) illustrates a case where the Emissions Level Effect is zero or even possibly negative, and B) shows that if we shut off differences in emission rates (approximately) to zero out the Emissions Level Effect, and shut off differences in county-specific damages to zero out the Emissions Location Effect, then congestion does not affect the marginal environmental value of wind, precisely as expected.

The above results make a strong case that uncongested markets increase the environ-

during congested hours, which likely reflects within-technology differences in NO_x emissions from natural gas generations (e.g. combined cycle versus turbines).

[18] This could be noise, or it may reflect differences in CO_2 emission rates of CC vs CT. For example, congestion may lead marginal wind generation to offset inefficient, dirtier CT plants in ERCOT West, whereas that same wind generation would offset more efficient CC plants in ERCOT North in the absence of congestion constraints.

mental value of wind, primarily through larger reductions in local pollutants. A reasonable interpretation of this finding is that when ERCOT markets are congested, wind power located primarily in ERCOT West is unable to offset fossil generators in the more populated eastern part of the state. In contrast, when uncongested, wind power in ERCOT West is more valuable as it can offset dirtier fossil generation in populated areas, particularly in Houston where the marginal damages from fossil generation are very large (Figure 4).

4.3 Robustness checks

Next, we consider a series of robustness exercises. The base specification classifies congested market conditions as hours where the average price spread across zones was greater than \$1. While this cutoff is somewhat arbitrary, we can examine whether varying this cutoff affects the estimated environmental value of wind. There are likely classification error tradeoffs in either direction. Lowering the cutoff means some hours where the market was basically uncongested will be classified as congested, while raising the cutoff means some hours where at least some portion of the market was congested will be classified as uncongested. Columns (1)-(5) of Appendix Table B.4 set the cutoffs for congested hours at \$0, \$0.1, \$0.5, \$3 and \$5, respectively. Regardless of the cutoff, results are similar to those above, with similar total damages avoided per MWh of wind in uncongested and congested hours.

We also examine alternative ways of defining the *Congested* variable in Equation 9. First, Appendix Table B.5 defines three pairwise *Congested* variables, corresponding to whether the price spread between ERCOT West and each of the other three zones exceeds \$1. That is, $C^{j}_{hdmy} = 1(|P_{West,hdmy} - P_{j,hdmy}| > c)$, where j is North, South, and Houston. Second, Appendix Table B.6 defines a single *Congested* variable based solely on the price spread between the noted zones in each column, $C^{ij}_{hdmy} = 1(|P_{i,hdmy} - P_{j,hdmy}| > c)$, where i, j index each of the zones. Results are consistent with the base model presented in Table 2.

Finally, while our base specification assumes solely contemporaneous effects between wind and environmental damages, wind generation at hour t may hypothetically affect power plant operations at some point $t + n$ in the future, e.g. due to ramping or effects on emission control technologies (Kaffine et al. 2013). To capture any intra-day spillovers between hours, Appendix Table B.8 aggregates to the daily level (Novan 2015), yielding estimates of environmental damages avoided that are very similar to the hourly estimates.

4.4 Mechanisms

Recall a reasonable explanation for the increased value of wind in uncongested conditions is that transmission allows wind generated in ERCOT West to offset generation in more populated areas to the east. Table 6 presents estimates of Equation 9 using total environmental damages by zone as the dependent variable, and the results are consistent with the above story. Focusing on the coefficient on $Wind \cdot Congested$, it is positive and economically and statistically significant for ERCOT Houston, implying smaller environmental benefits in ERCOT Houston when markets are congested. In contrast, for ERCOT West, the interaction coefficient is negative and significant, implying larger environmental benefits in ERCOT West from wind when markets are congested. Due to population differences, there is ultimately a net reduction in environmental damages avoided during congested periods.[19]

We can further show the consistency of the general story by drilling down to specific coal

[19] Given the large amount of coal capacity in ERCOT North and the large population center in Dallas/Fort Worth, it may be surprising that shifting fossil response in ERCOT North does not contribute more to the environmental value of wind. However, in contrast to ERCOT Houston, the coal plants in ERCOT North are not located in the DFW metropolitan area.

plants – the W.A. Parish coal plant (four units with a total capacity of 2.7 GW) which is located in the Houston suburbs (metro population 6.7 million) and is the only coal plant in the Houston zone and the Oklaunion coal plant (a single unit with 720 MW capacity) which is in Wilbarger County ('metro' population 13,000) and is the sole coal plant in the West zone. Table 7 estimates generation and environmental damage responses to wind in uncongested and congested periods at these two plants, yielding estimates consistent with the story above. Oklaunion is twice as responsive to wind in congested hours, while W.A. Parish is half as responsive when transmission constraints limit the ability of ERCOT West wind to influence fossil generation in ERCOT Houston.

Given wind resources are primarily located in ERCOT West, one might assume that congestion predominantly arises as large levels of wind generation drive down prices in the West relative to the rest of ERCOT. While this does happen frequently, it is important to note that from Table 1, prices in ERCOT West are on average *higher* than other regions. Examining this issue more closely, prices in ERCOT West exhibit greater volatility than other regions, with both very low and very high prices occurring more frequently than other regions. As such, the $Congested$ variable defined above represents hours when markets are congested because West prices are either higher or lower than the rest of ERCOT. Note however, regardless of whether prices are higher or lower in the West, when markets are congested, the presence of transmission congestion implies wind generation in the West will likely offset fossil generators in the West.

To explore this issue in more depth, we separate our congested variable into two mutually exclusive dummies indicating whether the market is congested and ERCOT West prices are lower than average ($NegCongested$) or if the market is congested and ERCOT West prices are higher than average ($PosCongested$). The market is congested in 38% of hours, with about half the hours negatively congested and half the hours positively congested across the sample.[20] Table 8 reports estimates of Equation 9 with $Wind$ interacted with both $NegCongested$ and $PosCongested$. Consistent with our hypothesis that, in congested hours, wind will tend to offset West generation regardless of the sign of the price spread, the environmental value of wind is similar across both negatively and positively congested hours despite reflecting very different states of the market.

4.5 Heterogeneous effects

To further explore the impact of congestion on the environmental value of wind, we examine the heterogeneity in damages avoided across three temporal dimensions: yearly, seasonally, and hourly. During the time period of our sample, there were substantial changes in the electricity sector due to transmission expansions such as CREZ, growth in renewable generation, and variation in fuel prices. As such, if our results were driven by a single year, this may raise concerns that some omitted variable was biasing our findings. In Table 9, the base model is estimated separately by year. Consistent with the above results, in uncongested hours wind typically has an environmental value on the order of \$50 dollars/MWh across years, while in congested hours, the environmental value is reduced by around \$13 dollars/MWh.

Next, one concern might be that unobserved outages due to plant maintenance may affect both the probability the market is congested and the dispatch order (and thus emissions). In particular, if this shift in the dispatch order due to plant maintenance tended to

[20] While on average the relative frequency of negative and positive congestion are roughly equal, this does change over time. In 2011, negative congestion occurs twice as often as positive congestion, while in 2012, positive congestion occurs about 50% more often than negative congestion.

increase emissions, this would positively bias the $Wind \cdot Congested$ coefficient, exaggerating the diminished environmental value of wind in congested market conditions.[21] Scheduled maintenance typically occurs during the "shoulder" months outside of the winter and summer peak load months. In Table 10, we split the sample into shoulder months (March, April, October, November) and non-shoulder months. The environmental value of wind in uncongested conditions is identical across shoulder and non-shoulder months, and the coefficient on $Wind \cdot Congested$ is actually larger in non-shoulder months, though not statistically distinguishable ($p = 0.143$ for total damages).

Finally, because different fossil units are marginal during different hours of the day, the environmental value of wind will also likely vary by hour of day. Figure 5 plots the environmental value of wind by hour for uncongested (solid) and congested (dashed) market conditions. The general pattern is consistent with prior work (e.g. Kaffine et al. (2013) and Novan (2015)) whereby wind is more environmentally valuable in low demand, overnight hours when coal is more likely to be the marginal generator. The environmental value of wind declines in congested hours, by as much as \$15 per MWh at midnight. This is roughly equivalent to the difference between the environmental value of wind in mid-day versus overnight hours in uncongested conditions. While the prior literature has noted the importance of the fact that the environmental benefits from wind depend on whether coal or gas is marginal at different times of day, this figure shows the effect of transmission constraints and market congestion can be of an approximately equivalent magnitude.

[21] This may occur if, for example, a pivotal natural gas plant temporarily closed and its closure increased periods of congestion while also increasing emissions if its foregone generation is compensated for by increased generation from coal plants. However, if a pivotal coal plant closes and it also leads to more congestion, while at the same time its foregone generation is replaced with cleaner gas-fired generation, emissions may fall and $Wind * Congested$ is biased toward zero. At the outset either of these situations may occur. As such, it is not clear that there is systematic bias in a consistent direction.

4.6 Total effects of the *Congested* variable

Beyond directly affecting emissions damages, wind can indirectly affect damages via the probability that ERCOT markets are congested. Consider a model of emission damages conceptually similar to Equation 9 that explicitly recognizes that congestion depends on wind generation:

$$D(W) = \beta_1 W + \beta_2 W * C(W) + \beta_3 C(W). \tag{10}$$

Then the total derivative of damages with respect to wind is:

$$\frac{dD}{dW} = \big(\beta_1 + \beta_2 C(W)\big) + (\beta_2 W + \beta_3)\frac{dC}{dW}. \tag{11}$$

The first term is the effect discussed in detail above, capturing the direct effect of wind on environmental damages in uncongested β_1 versus congested hours $\beta_1 + \beta_2$. The second term captures the indirect effect through changes in market congestion ($\frac{dC}{dW}$).

To gain a sense of the empirical magnitude of this indirect effect, Appendix Table B.2 estimates a series of specifications analogous to Table 2 (Columns (1)-(4)), but where *Congested* is the dependent variable of a linear probability model and *Wind* is our variable of interest. Across specifications, this coefficient is remarkably consistent.[22] Taking mean wind levels from Table 1, estimates of β_2 and β_3 from Table 2, and the estimate of $\frac{dC}{dW}$ from Column 4 of Appendix Table B.2, the second term is equal to: $(\beta_2 W + \beta_3)\frac{dC}{dW} = (10.37 * 3825 - 53812) * 0.0000465 = -\$0.66/\text{MWh}$ ($\pm\$0.48/\text{MWh}$). That is, at the mean wind generation level, the indirect effect of wind on damages through changes in the probability the market is congested is less than a dollar per MWh, or an order of magnitude or two smaller than the main effects.

[22] Alternative specifications and estimating approaches yielded very similar estimates on the order of 10^{-5} per MWh of wind generation.

5 MISO Results

The MISO market region covers a large swath of the middle of the US (see Figure 6) and much of the region's wind capacity and genration is concentrated in Iowa, southern Minnesota, and other more westerly areas of the MISO region, far from several key demand centers in the east portion of the market.[23] Given this spatial pattern of renewable generation, we would expect that during periods when MISO faces transmission congestion, much of the wind will offset fossil-fuel generation in the western regions, where the environmental value of emissions avoided is lower. Thus, as with ERCOT, the environmental value of wind generation is likely reduced during periods of market congestion. To test this assertion, we conduct a similar analysis using data from MISO. The "total damage" dependent variable for MISO is formed in the same way as it was for ERCOT.[24] Hourly wind generation for all of MISO is reported on MISO's website (www.misoenergy.org). Zonal prices and load are quoted for the northern portion of MISO based on the zones depicted in Figure 6.[25] Note given this spatial dissagregation, much of the wind capacity is concentrated in Zone 3, but the major demand centers are in the eastern zones. In addition, we also create an average gas-to-coal fuel price ratio in the same manner as described above for the ERCOT. Summary statistics for the MISO region data are provided in Appendix Table B.9.

[23] Note, MISO expanded in 2013 to include territories in Arkansas, Mississippi, Lousiana, and Texas, but we exclude these regions from our analysis and instead focus on the wind-rich norther portion of the market.

[24] For PM2.5 emissions coefficients, we again regress the sum of county-level PM2.5 emissions in counties with MISO generators on MISO generation by technology type to get technology-specific PM2.5 emission coefficients. We get separate coefficients for plants burning coke, non-lignite coal, lignite coal, and diesel, as well as for combined cycle gas and single cycle gas plants.

[25] The zonal prices were accessed directly from the Market Reports Archive section of the MISO website and zonal load data was accessed through ABB. Because load and price data were available for each of the utility regions of zone 7 (Consumers Energy (CONS) and Detroit Edison (DECO)) we treat that zone as two separate zones, bringing the total to eight zones where the CONS region is zone 7 and DECO is zone 8. Also, our zonal load is only available through 2014, but total load for the northern portion of MISO was available for 2011-2015 on the Market Reports Archive section of the MISO website.

The formation of the congestion dummy is done slightly differently for our MISO analysis given how the prices are quoted. MISO publishes the congestion, line-loss cost, and zonal electricity price separately, whereas all three of these components are embedded in the quoted zonal price in ERCOT. The congestion price gives the shadow value of the transmission constraint for the zone, where positive congestion prices reflect that the flow of power into the zone is restricted and a negative price reflects restrictions in power flows out of a zone. We use these quoted congestion prices in MISO to define the congestion dummy. We define the market as congested if one of the zonal congestion prices falls outside some price range. Formally, the congestion dummy, C_{hdmy}, in MISO is defined as:

$$C_{hdmy} = 1(congest_{min,hdmy} < -c \quad \text{OR} \quad congest_{max,hdmy} > c) \tag{12}$$

where $congest_{min,hdmy}$ is the minimum of the eight congestion prices in a given hour, $congest_{max,hdmy}$ is the maximum of the congestion prices in a given hour, and c is the user defined cutoff value. Over our sample, the mean $congest_{min,hdmy}$ and $congest_{max,hdmy}$ are about -\$8 and \$7, respectively. We initially choose a somewhat small cutoff value of $c = \$4$, though we vary this to check for the sensitivity of our results. Finally, beyond wind, the congestion dummy, and load, we also control for temperature with state-specific hourly temperature averages and power imports/exports into and out of MISO through MISO's major interconnections.[26]

Parameter estimates from MISO-specific variations of Equation 9 are given in Table 11. As expected, the results display a similar pattern to those for ERCOT where the marginal environmental value of wind decreases during congested periods. The loss during congested periods is economically and statistically significant, with the marginal value of wind falling

[26] MISO's Market Data Archive reports net flows at the major "interfaces" that connect MISO to other market regions. We control for net flows across the following interface abbreviations: EEI, IESO, MHEB, PJM, SWPP, TVA, WAUE, and OTHER.

by about 8-13% in congested hours. The results also indicate that wind generation is more environmentally valuable in MISO compared to ERCOT. This again is expected given that MISO has considerably more coal-fired generation than ERCOT. Similar to the ERCOT results, in comparing the local versus CO_2 damages (see Table 12), we see that congestion has a much larger effect on damages from local pollutants and that if one assesses the role of congestion on the environmental value of wind using a region-wide average (or median) estimate for per-unit damages from local pollutants, the impacts of congestion are much smaller and statistically insignificant. This again highlights the need to consider spatially explicit damages when considering the interaction of renewable generation and congestion.[27]

6 Implications and additional considerations

Recall, during our sample period, over $7 billion was spent to increase the amount of transmission capacity connecting ERCOT's wind-rich West zone with the load centers to the east. While the CREZ transmission upgrades clearly have had important impacts on prices (LaRiviere and Lu 2017), our above analysis suggests the expansion also has important non-market consequences as well. To put our results into perspective, this section examines the impacts of transmission expansion on the environmental value of wind.

To shed light on how much the environmental value of wind generation increased as a result of the CREZ transmission expansions, we first need to quantify how much the CREZ upgrades reduced the frequency of congestion. Causally measuring this effect is challenging

[27] We also considered specifications with higher and lower cutoff values for the determination of a congested hour (Appendix Tables B.10 and B.11). Results with a higher cutoff value for *Congested* = 1 returned numerically similar results to those presented here. Lowering the cutoff value slightly also returned similar values, but considerably lower cutoff limits often returned statistically insignificant parameter estimates, which is to be expected as this results in almost all hours being classified as congested.

given that the new CREZ lines were steadily energized over the sample peirod (Figure 7). Nonetheless, to produce a back-of-the-envelope estimate, we first compare the unconditional congestion frequency in 2011-2012 (pre-CREZ) versus 2014-2015 (post-CREZ). Markets were congested roughly half the time (49.7%) in 2011-2012, and that fell by half (25.3%) in 2014-2015, or a decline in congestion of 24.3 percentage points. Using the coefficient estimates in Table 2, 2015 average hourly wind generation of 4,649.3 MWh, and the unconditional change in the probability of congestion suggests a roughly $135 (OLS) to $250 (IV-LASSO) million annual increase in the environmental value of wind due to increased market integration.

However, this simple approach fails to account for changing market conditions. Specifically, average hourly wind generation grew by over 40% from 2011 to 2015. To account for this we regress the hourly indicator of congestion ($Congested_h$) on hourly wind generation, zonal load, fuel prices, SPP load and wind, the square of each of the preceding controls, hour-by-month and day-of-week fixed effects, a dummy for 2013 observations (when CREZ was partially completed), and a dummy for 2014 and 2015 observations (when CREZ was essentially completed). The parameter on the year 2014 and 2015 dummy was -0.45, with standard errors of 0.07, suggesting that, after conditioning on market conditions, the probability of being in a congested hour fell by 45 percentage points after CREZ. This conditional decline in congestion from 2011-2012 to 2014-2015 leads to a roughly $240 (OLS) to $450 (IV-LASSO) million dollar increase in the annual environmental value of wind due to increased market integration, based on 2015 averages. The bulk of this increase, 73% (IV-LASSO) and 85% (OLS), comes from decreased local pollutant damages.

Of course, CREZ may have done more than simply lower the frequency of grid congestion. For instance, CREZ is frequently credited with reducing the frequency and amount of potential wind generation that is curtailed. In 2012, ERCOT reported average wind generation curtailment rates of about 4% of actual generation and that rate fell to nearly 1% in 2015. If we attribute all of that reduced curtailment to CREZ, then based on 2015 average wind generation values and congestion rates, the environmental value of the reduced curtailment is about $62 million annually, using the main OLS estimate.[28] CREZ is also often credited with increasing wind generation capacity. It is true that wind generation capacity did expand quite rapidly after CREZ was completed, with capacity gains of about 4.7 GW from 2013 to 2015. However, over this period, MISO and the Southwest Power Pool, the other ISOs with considerable wind capacity, also added large amounts of wind generating capacities, about 3 GW and 4 GW, respectively. These additions, and likely a large share of the additions in ERCOT, were generally seen as motivated by the desire to get new wind farms completed before the federally funded production tax credit was reduced.

Ultimately, the back-of-the-envelope estimates suggest that the CREZ transmission upgrades increased the environmental value of ERCOT wind generation by well in excess of $240 million per year. More generally, the empirical estimates from the ERCOT and MISO case studies highlight how increasing transmission capacity between renewable-rich and demand-rich regions serves to increase the environmental value of renewable generation. It also stands to reason that this complementarity runs in the other direction as well – i.e. the environmental value of transmission capacity increases with more renewables on the system.[29] As

[28] Wind generation in 2015 was 37% higher than in 2012, so 2012 curtailment rates may have been higher had 2012 had 2015 wind levels. Assuming curtailment rates in 2012 were also 37% higher than observed, the environmental value of the reduced curtailment would be about $83 million annually.

[29] This follows from our simple theory model as well. If Q increases, F_e falls and F_w increases in otherwise congested periods. If global emission rates are similar in the regions, but local pollutants cause more damage in the east than the west, increased transmission will reduce environmental damages. Those reductions should be larger in periods with greater wind generation as the wind generation offsets increases in F_w that come with increased Q. Of course this is predicated on flows being from west to east, which, in practice, is

noted above, the CREZ expansion in ERCOT does not provide a perfect setting to test this conjecture given the multi-year rollout of the expansion. However, roughly 60% of the transmission project was completed during the last half of 2013 (see Figure 7).[30] This relatively short window of substantial transmission expansion gives us an opportunity to run an event study (of sorts) where we can examine how environmental damages differ after versus before the jump in transmission capacity at different levels of wind generation.

Estimates of the following model are made separately using pre- and post-jump samples:

$$D_{hdmy} = \beta_0 + \beta_1 W_{hdmy} + \sum_i \theta_i^j f_i(X_{hdmy}) + \gamma_{hm} + \delta_d + \epsilon_{hdmy}, \tag{13}$$

where D_{hdmy} is the hourly ERCOT-wide damage, W_{hdmy} is the hourly ERCOT wind generation, and $f_i(X_{hdmy})$ is again a function of control variables that include linear and quadratic specifications of zonal load, SPP load and wind, and the average Texas temperature. We again include hour-by-month (γ_{hm}) and day-of-week (δ_d) fixed effects. We define the year spanning June 30, 2012 through June 30, 2013 as the pre-jump period and January 3, 2014 through January 3, 2015 as the post-jump period. These two sample periods are shown as the shaded regions in Figure 7 and, as can be seen, exclude the roughly six month period where CREZ progresses from roughly 40% to 100% completed. As expected, the probability of being a congested hour (as defined for our base specification in the ERCOT analysis) drops considerably from the pre-jump rate of about 48% to the post-jump rate of 30%.

Using the estimates of Equation (13), we predict the pre- and post-jump average hourly environmental damage across a range of wind generation values.[31] Figure 8 displays the

not always the case in ERCOT or other regions.

[30] Figure 7 plots the share of CREZ completed based on miles of line completed. We consider a line segment completed on the date the line was energized according to project data provided to us by ERCOT.

[31] Summary statistics and point estimates on each sample are reported in Appendix Tables B.12 and B.13.

predicted pre- and post-jump hourly damages and the corresponding 95% confidence intervals. The figure again depicts a complementary relationship between transmission and renewables with respect to environmental damages. With low levels of wind generation, the increased transmission capacity provides little or no environmental value. We might expect this because while transmission may allow less damaging fossil fuel generation in the west to supplant high-damage generation in the east, with low wind values we will also have hours where prices are higher in the east than the west. The increased transmission in these instances promotes a flow of power from east to west, supplied by increased production from higher-damage fossil fuel units located near population centers. Conversely when wind generation is high, generation flows will typically be from west to east, and increased transmission will facilitate more substitution from high-damage fossil fuel in the east with lower-damage fossil fuel in the west – or even with wind generation itself in the west.[32] Accordingly, we find that the environmental damages are predicted to be lower with high wind in the post-jump period than in the pre-jump period.[33]

7 Conclusion

The growth of renewable electricity resources, particularly onshore wind, has spurred substantial private and public interest in increasing transmission capacity to move electricity

For the remaining controls in 13, the prediction of environmental damages are made with these variables at their respective mean values over the two samples combined.

[32] We do observe hours where prices are negative in the West zone of ERCOT, suggesting that wind is the marginal generator. In these hours, increased transmission would supplant fossil generation in the east with zero-emission wind generation in the west.

[33] Beyond simple linear specifications, we also considered specifications where wind enters Equation 13 as second and third order polynomials. In addition, we considered a pre-jump sample as the six months before 6/30/2013 and the post-jump sample as the six months from 01/03/2014 on. Results from these specification are qualitatively the same as presented here; the difference in predicted damages between the pre- and post-jump samples are very similar at low values of wind, but at high values of wind generation, the post-jump predicted damages are noticeably lower than the pre-jump predictions.

from renewable-rich areas to demand centers. While such projects are usually advocated on the grounds of market considerations such as arbitraging regional electricity prices or grid reliability, this paper highlights that these investments in transmission infrastructure also provide sizable non-market benefits.

First, we analytically highlight two key channels through which transmission congestion (or alleviation via transmission expansion), can affect the non-market value of wind - the Emissions Level and Location Effects. The Level Effect highlights that congestion alters which marginal fossil units respond to wind generation, affecting the level of emissions and damages avoided. The Location Effect describes how congestion can also change where wind-induced emission reductions occur, affecting damages from local pollutants. While the Level Effect has an ambiguous impact on the environmental value of renewables, the Location Effect likely leads to dramatic increases in the environmental value of renewables following transmission expansions. This stems from the fact that much of the investment in transmission capacity is designed to connect sparsely populated renewable-rich regions with much more heavily populated demand centers. Consequently, transmission expansions enable renewable generation to offset more fossil generation, and thus emissions, from larger population centers – precisely where emissions impose the largest damages.

To explore whether increases in transmission capacity increase the environmental value of renewables, we focus on two regional electricity markets in the United States – the Texas market (ERCOT) and the Mid-Continent market (MISO). The ERCOT and MISO markets are well suited for this analysis not only because they have the highest wind generation of all ISO/RTO regions, but more generally, they are a microcosm of the U.S., and many international energy markets, as a whole. Specifically, ERCOT and MISO both have wind-resource rich but demand-poor areas located relatively far from larger population centers.

Combining 2011-2015 hourly data on wind generation and emissions with county-level damages by pollutant, we find, based on our more generous OLS estimates, that during hours when the ERCOT market was congested (transmission capacity constraints were binding) an additional MWh of wind generation reduced total environmental damages from the electric sector by $40. However, during uncongested hours an additional MWh of wind reduced environmental damages by $53, a 31% increase in the non-market value of wind. The bulk of this increased value in uncongested periods stems from the Emission Location Effect. Specifically, when the market is uncongested, generation from wind turbines concentrated in the sparsely populated western portion of Texas offsets more production from high-damage fossil fuel units located near the population centers to the east (e.g., Houston). A similar pattern emerges in MISO; grid congestion reduces the environmental value of wind, as wind generation in western MISO areas such as Iowa and southern Minnesota is unable to offset fossil generation from demand centers in eastern MISO.

Using the estimates from ERCOT, we are able to provide back-of-the-envelope estimates of the non-market benefits provided by the CREZ project – a roughly $7 billion investment designed to increase transmission capacity between wind-rich west Texas and demand centers to the east. We estimate that the CREZ transmission upgrades, which markedly reduced the frequency of congestion, provided non-market benefits on the order of $240-450 million annually, similar in magnitude to the market benefits found in LaRiviere and Lu (2017).

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Table 1: Data Summary - ERCOT

	Mean	SD	Min	Max
CO_2 damage ($)	797,561	226,315	255,341	1,544,803
SO_2 damage ($)	909,958	263,344	168,715	1,575,828
NO_X damage ($)	51,066	17,428	12,765	132,068
PM2.5 damage ($)	77,783	24,337	23,573	173,553
West RTM Price ($)	35.62	86.94	-36.58	4,547.06
South RTM Price ($)	33.48	85.83	-29.19	4,381.70
North RTM Price ($)	32.00	80.02	-9.93	4,515.99
Houston RTM Price ($)	32.63	82.60	-21.28	4,371.75
Wind (MWh)	3,825	2,407	8.47	13,812
Congested	0.3808	0.4856	0	1
Total Load (MWh)	38,288	9,240	6,230	69,878
Fuel Price Ratio	0.0155	0.0039	0.0082	0.0528

Notes: 2011-2015 ERCOT. 43,824 hourly observations in total.

Table 2: Average marginal effect of wind generation on environmental damages

	(1)	(2)	(3)	(4)	(5)
	Total Dmg	Total Dmg	Total Dmg	Total Dmg	Total Dmg
Wind	-51.65***	-50.30***	-52.77***	-51.84***	-52.35***
	(3.314)	(1.647)	(1.905)	(1.823)	(1.887)
Wind*Congested	8.832***	12.10***	11.63***	9.791***	12.36***
	(2.968)	(2.117)	(1.980)	(1.795)	(2.263)
Congested	4,220	-62,095***	-58,751***	-50,393***	-239,890
	(15,731)	(9,603)	(9,228)	(8,500)	(387,872)
Load		69.27***	68.62***		
		(4.867)	(5.506)		
$Load^2$		-0.0004***	-0.0003***		
		(5.46e-05)	(6.43e-05)		
Fuelratio		5.015e+07***	5.172e+07***	5.209e+07***	
		(1.788e+07)	(1.701e+07)	(1.700e+07)	
$Fuelratio^2$		-8.589e+08***	-8.459e+08***	-8.369e+08***	
		(2.840e+08)	(2.675e+08)	(2.673e+08)	
Add'l controls	N	N	Y	Y	Y
Zonal load	N	N	N	Y	Y
Fully interacted	N	N	N	N	Y
N	43,824	43,824	43,824	43,824	43,824
R^2	0.817	0.912	0.914	0.916	0.919

*Notes: Coefficient on wind can be interpreted as \$/MWh. Congested = 1 if average price spread > 1 (38% of obs). Load is ERCOT-wide load. Fuelratio is average gas price/average coal price. Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Additional controls include linear and quadratic temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston loads. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 3: Average marginal effect of wind generation - IV estimates

	(1) Basic IV	(2) Lasso IV
Wind	-58.40***	-55.30***
	(2.930)	(3.166)
Wind*Congested	38.67***	22.33**
	(7.872)	(9.353)
Congested	-97,984	-137,669**
	(322,394)	(69,502)
Kleibergen-Paap rk Wald F stat	15.02	69.26
N	43,726	43,823
R^2	0.902	0.914

*Notes: For the "Basic IV" case instruments for Congested and Wind*Congested are: wind speed, wind direction, cloud cover, percent of CREZ completion, interactions of the previous with wind generation, and interactions of the previous with total load. "LASSO IV" is based on a post-LASSO estimation where a LASSO algorithm is used to select among 1550 possible instruments. Stock-Yogo weak identification cut-off for 10% max bias is 10.96. Coefficient on wind can be interpreted as $/MWh. Congested = 1 if average price spread > 1 (38% of obs). Hour-by-month, month-by-year, day of week fixed effects, zonal load, and other controls are included for all specifications. Control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 4: Average marginal effect of wind generation - local vs global

	(1) Local Dmg	(2) Local Dmg (IV-LASSO)	(3) CO_2 Dmg	(4) CO_2 Dmg (IV-LASSO)	(5) Local Dmg (average)	(6) Local Dmg (median)
Wind	-30.50***	-32.13***	-21.86***	-23.17***	-24.68***	-17.43***
	(1.682)	(2.841)	(0.427)	(0.771)	(1.352)	(0.931)
Wind*Congested	10.59***	16.56**	1.762***	5.767**	7.879***	5.390***
	(2.015)	(8.105)	(0.463)	(2.245)	(1.753)	(1.208)
Congested	-158,628	-101,719*	-81,262	-35,950**	-333,238	-207,343
	(345,657)	(58,816)	(60,549)	(16,820)	(233,990)	(160,697)
N	43,824	43,823	43,824	43,823	43,824	43,824
R^2	0.822	0.813	0.985	0.983	0.875	0.874

*Notes: Coefficient on wind can be interpreted as $/MWh. Congested = 1 if average price spread > 1 (38% of obs). Columns (5) and (6) replace county-specific local pollutant damages with state-wide average and state-wide median values, respectively. Columns (2) and (3) instrument for Congested and $Wind - Congested$ using the IV-LASSO technique. Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Control variables in all specifications include linear and quadratic: average gas price/average coal price, temperature, SPP wind, SPP load, and linear and quadratic zonal load controls for ERCOT West, North, South and Houston loads. All specifications are fully interacted models, which interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 5: Average marginal effect of wind generation - levels versus location

	(1) CO_2 Dmg	(2) CO_2 Dmg	(3) Local Dmg	(4) Local Dmg	(5) Local Dmg (median)	(6) Local Dmg (median)
Wind	-18.31***	-16.63***	-13.69***	-9.999***	-10.07***	-7.162***
	(0.783)	(0.889)	(2.475)	(3.117)	(1.564)	(2.425)
Wind*Congested	-0.499	-2.109*	3.505	2.327	2.090	0.639
	(0.877)	(1.059)	(3.072)	(3.529)	(2.038)	(1.978)
Congested	-124,776	-171,482	-964,930**	-863,633*	-291,622	-199,320
	(95,801)	(105,579)	(378,037)	(503,858)	(219,423)	(315,297)
N	9,958	5,182	9,958	5,182	9,958	5,182
R^2	0.988	0.988	0.790	0.808	0.864	0.868

*Notes: Coefficient on wind can be interpreted as $/MWh. Congested = 1 if average price spread > 1. Columns (1), (3) and (5) restrict the sample to observations where the ERCOT West coal plant capacity factor exceeds 0.80. Columns (2), (4), and (6) restrict the sample further to observations where ERCOT West and North electricity prices exceed $35. Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Control variables in all specifications include linear and quadratic: average gas price/average coal price, temperature, SPP wind, SPP load, and linear and quadratic zonal load controls for ERCOT West, North, South and Houston loads. All specifications are fully interacted models, which interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 6: Average marginal effect of wind generation - zonal impacts

	(1) Total Dmg Houston	(2) Total Dmg North	(3) Total Dmg South	(4) Total Dmg West
Wind	-23.29***	-18.55***	-9.441***	-1.607***
	(1.619)	(0.855)	(0.500)	(0.166)
Wind*Congested	8.921***	3.090***	1.922**	-0.891***
	(2.171)	(1.114)	(0.749)	(0.188)
Congested	179,441	-143,125	-276,999***	76,495***
	(329,759)	(126,442)	(98,283)	(19,774)
N	43,824	43,824	43,824	43,824
R^2	0.731	0.898	0.892	0.728

*Notes: Coefficient on wind can be interpreted as $/MWh. Congested = 1 if average price spread > 1 (38% of obs). Each column represents damages from generation in the noted ERCOT zone.Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Control variables in all specifications include linear and quadratic: average gas price/average coal price, temperature, SPP wind, SPP load, and linear and quadratic zonal load controls for ERCOT West, North, South and Houston loads. All specifications are fully interacted models, which interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 7: A tale of two coal plants: Oklaunion and W A Parish

	(1)	(2)	(3)	(4)
Panel A: All observations				
	Oklaunion Generation	W A Parish Generation	Oklaunion Damages	W A Parish Damages
Wind	-0.0109***	-0.0669***	-0.223***	-19.15***
	(0.00206)	(0.00453)	(0.0420)	(1.297)
Wind*Congested	-0.00919***	0.0316***	-0.187***	9.038***
	(0.00242)	(0.00667)	(0.0493)	(1.908)
Congested	943.0***	371.2	19,224***	106,269
	(294.3)	(988.5)	(5,999)	(282,948)
N	43,824	43,824	43,824	43,824
R^2	0.631	0.730	0.631	0.730
Panel B: Hours with positive generation				
	Oklaunion Generation	W A Parish Generation	Oklaunion Damages	W A Parish Damages
Wind	-0.0152***	-0.0693***	-0.311***	-19.85***
	(0.00169)	(0.00463)	(0.0345)	(1.325)
Wind*Cong	-0.0121***	0.0341***	-0.246***	9.765***
	(0.00255)	(0.00644)	(0.0521)	(1.843)
Congested	521.8**	708.1	10,637**	202,685
	(240.1)	(1,199)	(4,894)	(343,251)
N	35,488	26,762	35,488	26,762
R^2	0.631	0.720	0.631	0.720

*Notes: Coefficient on wind can be interpreted as MWh of coal/MWh of wind for Generation, and $/MWh of wind for Damages. Panel A includes all observations (including zero generation), while Panel B restricts the sample to hours with positive generation. Congested = 1 if average price spread > 1 (38% of obs). Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Control variables include linear and quadratic : average gas price/average coal price, temperature, SPP wind, SPP load, and linear and quadratic zonal load controls for ERCOT West, North, South and Houston loads. All specifications are fully interacted models, which interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 8: Average marginal effect of wind generation - positive vs negative price spreads

	(1) Total Dmg	(2) Local Dmg	(3) CO_2 Dmg
Wind	-52.93***	-31.13***	-21.87***
	(1.932)	(1.731)	(0.426)
Wind*NegCongested	16.72***	14.78***	1.849***
	(3.093)	(2.767)	(0.670)
Wind*PosCongested	12.78***	10.86***	1.724***
	(2.575)	(2.333)	(0.510)
NegCongested	-253,575	-177,484	-77,055
	(402,019)	(356,928)	(61,864)
PosCongested	-219,727	-144,105	-76,385
	(400,603)	(356,049)	(61,994)
N	43,824	43,824	43,824
R^2	0.916	0.818	0.985

*Notes: Coefficient on wind can be interpreted as $/MWh. NegCongested = 1 if average price spread > 1 and ERCOT West price is below ERCOT average (19.5% of obs). PosCongested = 1 if average price spread > 1 and ERCOT West price is above ERCOT average (18.6% of obs).Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Control variables in all specifications include linear and quadratic: average gas price/average coal price, temperature, SPP wind, SPP load, and linear and quadratic zonal load controls for ERCOT West, North, South and Houston loads. All specifications are fully interacted models, which interacts all controls (including fixed effects) with NegCongested and PosCongested variables. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 9: Average marginal effect of wind generation on environmental damages by year

	2011 Total Dmg	2012 Total Dmg	2013 Total Dmg	2014 Total Dmg	2015 Total Dmg
Wind	-67.95***	-54.53***	-46.88***	-50.92***	-51.39***
	(4.538)	(5.045)	(4.379)	(3.221)	(2.762)
Wind*Congested	24.53***	11.91**	14.58***	14.13***	11.27***
	(6.091)	(5.126)	(5.056)	(4.022)	(3.182)
Congested	1.068e+06	1.655e+06*	2.982e+06*	119,153	-2.933e+06***
	(665,191)	(885,857)	(1.562e+06)	(825,649)	(1.067e+06)
N	8,760	8,784	8,760	8,760	8,760
R^2	0.925	0.914	0.899	0.916	0.946

*Notes: Coefficient on wind can be interpreted as $/MWh. Congested = 1 if average price spread > 1 (38% of obs). Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Control variables in all specifications include linear and quadratic: average gas price/average coal price, temperature, SPP wind, SPP load, and linear and quadratic zonal load controls for ERCOT West, North, South and Houston loads. All specifications are fully interacted models, which interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 10: Average marginal effect of wind generation - shoulder vs non-shoulder

	(1)	(2)	(3)
Panel A: Shoulder months			
	Total Dmg	Local Dmg	CO_2 Dmg
Wind	-53.38***	-31.45***	-22.00***
	(2.795)	(2.368)	(0.858)
Wind*Congested	11.34***	9.504***	1.727**
	(2.834)	(2.562)	(0.725)
Congested	536,481	591,454	-56,961
	(713,765)	(634,002)	(111,430)
N	14,640	14,640	14,640
R^2	0.835	0.711	0.960
Panel B: Non-shoulder months			
	Total Dmg	Local Dmg	CO_2 Dmg
Wind	-52.83***	-31.03***	-21.87***
	(2.641)	(2.410)	(0.444)
Wind*Cong	14.35***	12.36***	1.859***
	(3.246)	(2.822)	(0.595)
Congested	-415,048	-347,330	-67,939
	(485,268)	(431,961)	(77,574)
N	29,184	29,184	29,184
R^2	0.926	0.843	0.987
All controls	Y	Y	Y
Zonal load	Y	Y	Y
Fully interacted	Y	Y	Y

*Notes: Coefficient on wind can be interpreted as \$/MWh. Shoulder months are March, April, October, November. Congested = 1 if average price spread > 1 (38% of obs). Hour-by-month, month-by-year, day of week fixed effects included for all spefications. Control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 11: Average marginal effect of wind generation on environmental damages - MISO

	(1)	(2)	(3)	(4)	(5)
Wind	-55.34***	-83.20***	-82.93***	-84.48***	-85.85***
	(11.20)	(4.635)	(4.068)	(5.433)	(4.995)
Wind*Congested	-29.27***	10.58***	7.379**	6.822*	10.11***
	(10.27)	(3.430)	(3.018)	(4.000)	(3.625)
Congested	176,073***	-60,946***	-45,624***	-44,993***	-1.446e+06***
	(38,859)	(13,819)	(12,624)	(14,853)	(510,132)
Load		153.8***	135.4***		
		(11.64)	(11.16)		
$Load^2$		-0.000435***	-0.000310***		
		(8.69e-05)	(8.31e-05)		
Fuelratio		3.344e+07***	2.997e+07***	2.862e+07***	
		(1.017e+07)	(8.759e+06)	(1.009e+07)	
$Fuelratio^2$		-1.927e+08***	-1.735e+08***	-1.660e+08***	
		(5.715e+07)	(4.907e+07)	(5.838e+07)	
Add'l controls	N	N	Y	Y	Y
Zonal load	N	N	N	Y	Y
Fully interacted	N	N	N	N	Y
N	43,824	43,824	43,744	35,000	35,000
R^2	0.848	0.959	0.963	0.953	0.954

*Notes: All specifications include hour-month, month-year, and day-of-week fixed effects. Coefficient on wind can be interpreted as $/MWh. Load is the northern MISO-wide load. Fuelratio is average gas price/average coal price. Additional controls include linear and quadratic temperature and MISO import/exports at important interfaces. Zonal load includes linear and quadratic controls for 8 MISO zones described in the text. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 12: Average marginal effect of wind generation - MISO local vs global

	(1) Local Dmg	(2) CO_2 Dmg	(3) Local Dmg (average)	(4) Local Dmg (median)
Wind	-56.16***	-29.73***	-54.27***	-49.35***
	(4.732)	(0.734)	(4.236)	(3.865)
Wind*Congested	8.060**	1.958***	4.814	4.414
	(3.445)	(0.674)	(3.107)	(2.837)
Congested	-1.330e+06***	-104,048	-1.348e+06***	-1.229e+06***
	(469,348)	(86,944)	(383,821)	(350,257)
N	35,000	35,000	35,000	35,000
R^2	0.817	0.985	0.869	0.874

*Notes: Coefficient on wind can be interpreted as $/MWh. Congested = 1 if average price spread > 1 (38% of obs). Columns (3) and (4) replace county-specific local pollutant damages with northern MISO-wide average and median values, respectively. Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Control variables include linear and quadratic: average gas price/average coal price, temperature, MISO net imports, and linear and quadratic zonal load controls for the MISO zones described in the text. All specifications are fully interacted models, which interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

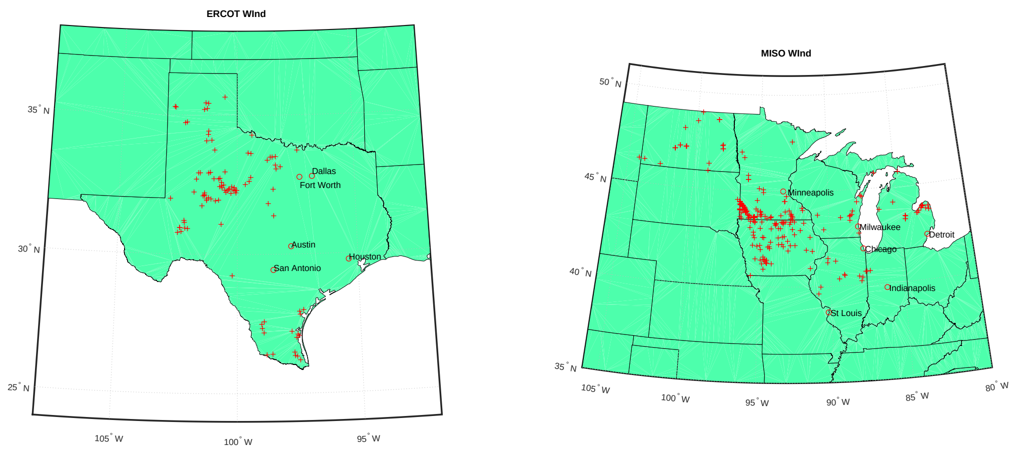

Figure 1: Location of wind farms in ERCOT and MISO (source: EIA 860 Form from 2015)

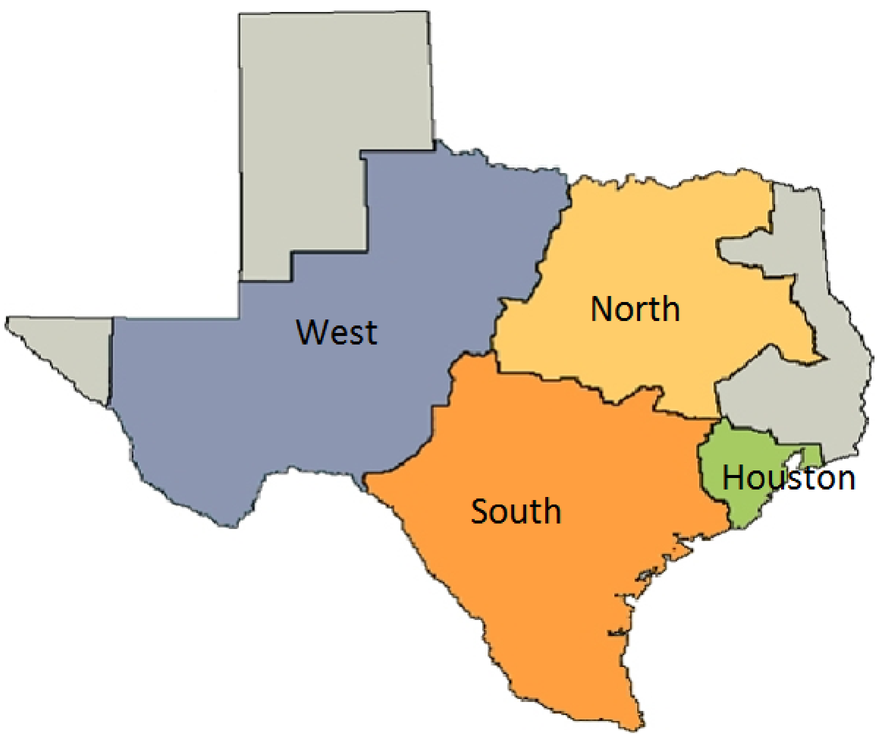

Figure 2: ERCOT zones (source: ERCOT)

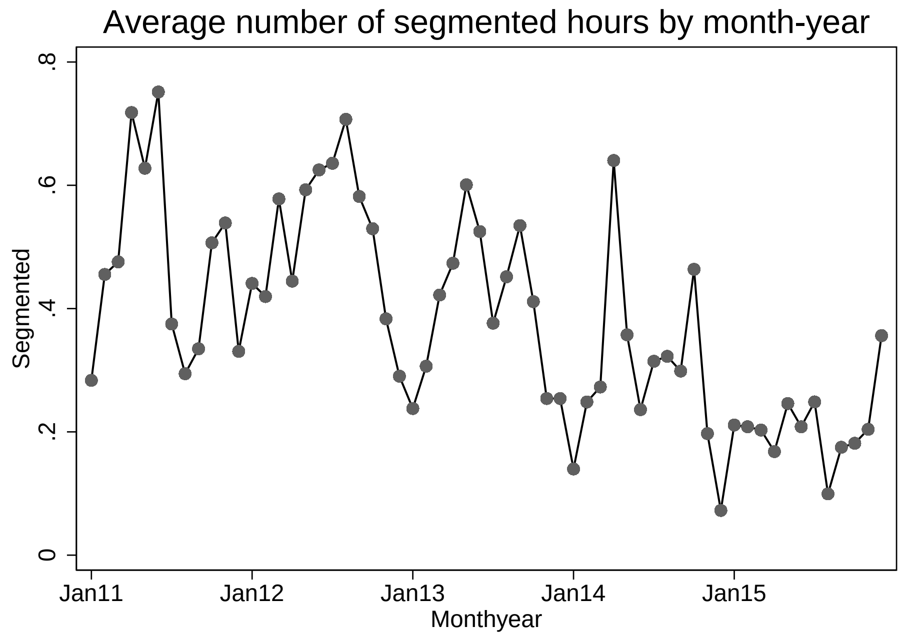

Figure 3: Time series variation in Congested hours in ERCOT.

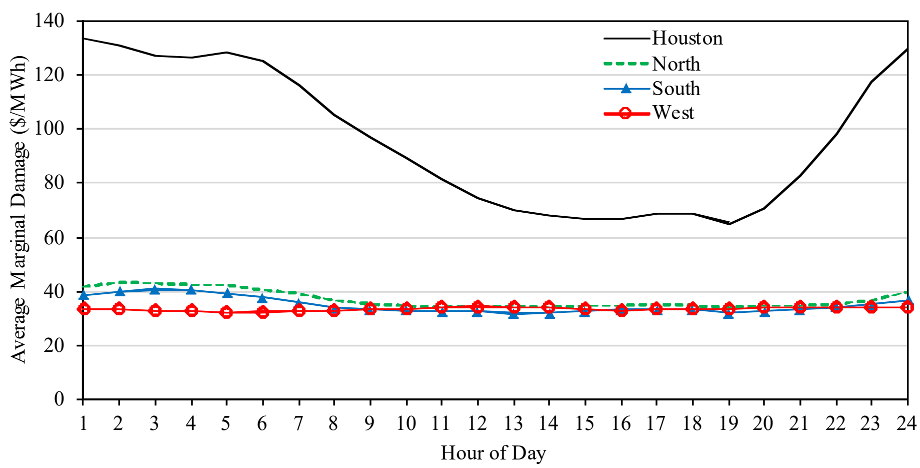

Figure 4: Damages from MWh of fossil generation across ERCOT zones.

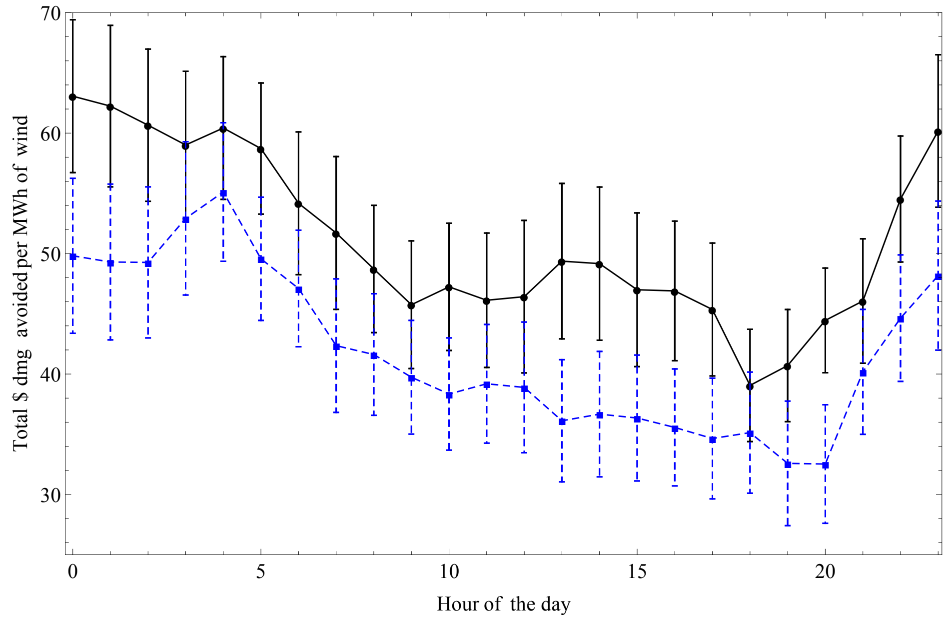

Figure 5: Environmental value of wind by hour in Uncongested (solid) and Congested periods (dashed) in ERCOT.

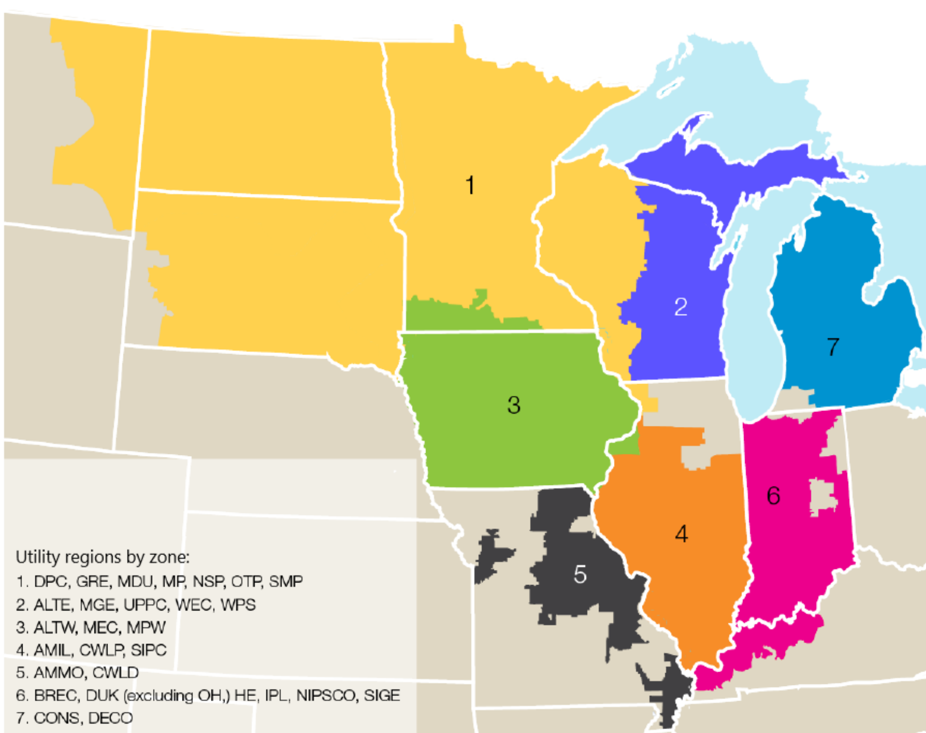

Figure 6: MISO Zones (source: MISO)

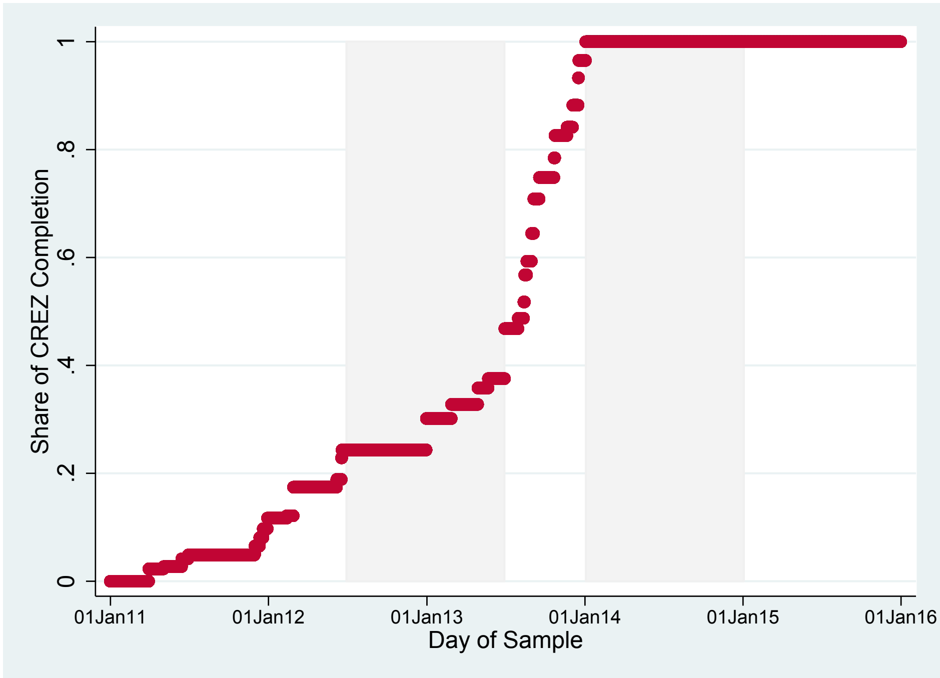

Figure 7: Share of CREZ completion with shaded pre-/post-CREZ jump samples (source: ERCOT)

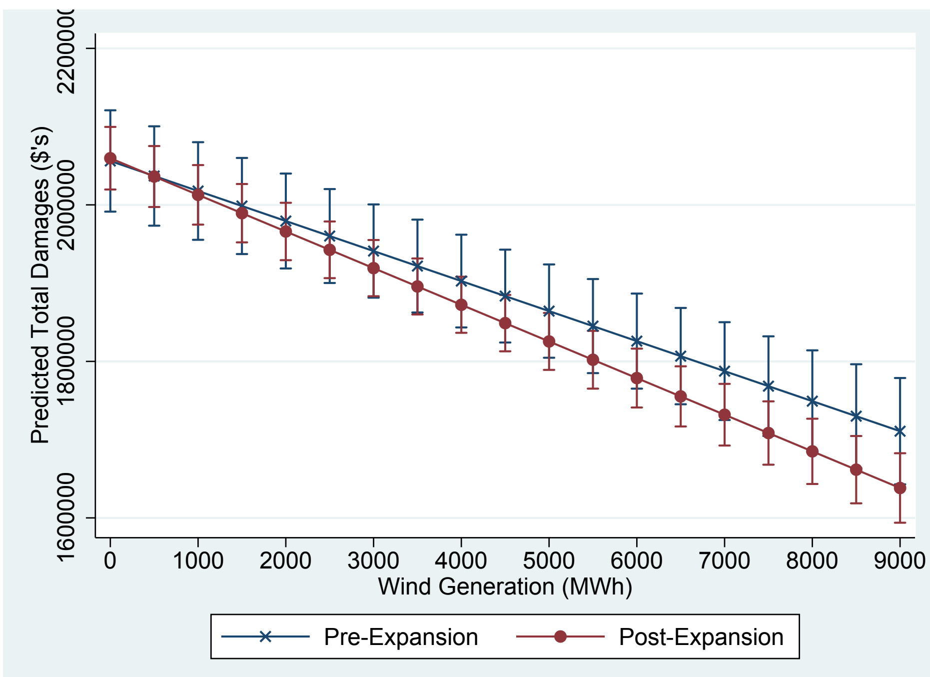

Figure 8: Predicted environmental damages in the pre-/post-CREZ jump samples versus varying levels of wind generation.

(Online Appendices)

A ERCOT and the CREZ expansion

Over the last decade, Texas has experienced rapid growth in wind generation. By the end of 2017, there was over 20,000 MW of wind capacity installed in the region overseen by the Electric Reliability Council of Texas (ERCOT). Texas wind development has been driven by a combination of factors. First, Texas was an early RPS adopter, passing renewable capacity mandates in 1999. Second, the state has faced high electricity prices for many years. Finally, Texas has excellent wind resources, particularly in the western portion of the state where the vast majority of wind turbines have been installed.

Integrating the surge of wind capacity into the ERCOT market has not been without its complications. While there are excellent wind resources in west Texas, the wind tends to be stronger during the low demand, nighttime hours. In addition to the temporal mismatch between wind generation and demand, there is also a spatial mismatch. The wind farms are predominantly in the west while the main ERCOT demand centers are located in the east. With very limited capacity to trade with the surrounding states, the western portion of the ERCOT market has become a large net-exporter of electricity to the eastern demand centers.

Initially, the ERCOT transmission network was not capable of supplying the glut of overnight wind generation from west Texas to the east. Real-time electricity prices in the western portion of the grid were often heavily depressed relative to the rest of the ERCOT market. In 2012, interval wholesale electricity prices rarely fell below $10/MWh in the North, Houston, and South regions. In contrast, in the West region, the interval prices regularly reached prices of \$0/MWh or lower – particularly in the high wind, low demand overnight hours.

Recognizing that consistently lower wholesale prices in west Texas would serve as a deterrent to continued investment in renewable capacity in the west, the Public Utility Commission of Texas mandated the construction of new transmission lines connecting the eastern demand centers with several wind rich regions in the west – called Competitive Renewable Energy Zones (CREZs). By 2015, over \$7 billion worth of CREZ transmission upgrades were completed. The 3,500-plus miles worth of new transmission lines were capable of exporting 18,500 MW of power from the wind-rich West region to the eastern demand centers.

B Appendix Tables and Figures

Table B.1: Average marginal effect of wind generation on emissions

	(1)	(2)	(3)	(4)
	SO_2 (lbs)	NO_x (lbs)	PM2.5 (lbs)	CO_2 (tons)
Wind	-1.513***	-0.571***	-0.0552***	-0.598***
	(0.0931)	(0.0308)	(0.00130)	(0.0115)
Wind*Congested	0.555***	-0.0805*	0.0102***	0.0482***
	(0.120)	(0.0473)	(0.00201)	(0.0127)
Congested	-18,392	3,518	-377.8*	-1,555
	(15,533)	(4,394)	(211.5)	(1,508)
Hour-Month FE	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y
All controls	Y	Y	Y	Y
Zonal load	Y	Y	Y	Y
Fully interacted	Y	Y	Y	Y
N	43,824	43,824	43,824	43,824
R^2	0.851	0.881	0.965	0.987

*Notes: Coefficient on wind can be interpreted as lbs or tons/MWh. Congested = 1 if average price spread > 1 (38% of obs). Hour-by-month, month-by-year, day of week fixed effects included. Control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table B.2: Average marginal effect of wind generation on Congested

	(1) Congested	(2) Congested	(3) Congested	(4) Congested
Wind	4.47e-05***	4.46e-05***	4.74e-05***	4.65e-05***
	(6.38e-06)	(6.28e-06)	(6.56e-06)	(6.63e-06)
Load		1.18e-05	1.05e-05	
		(7.06e-06)	(8.97e-06)	
$Load^2$		5.77e-11	9.20e-11	
		(8.44e-11)	(1.02e-10)	
Fuelratio		-16.13	-14.12	-13.12
		(14.92)	(15.59)	(15.35)
$Fuelratio^2$		369.2**	326.8*	291.4
		(176.6)	(181.5)	(180.4)
Hour-Month FE	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y
Add'l controls	N	N	Y	Y
Zonal load	N	N	N	Y
N	43,824	43,824	43,824	43,824
R^2	0.252	0.271	0.272	0.279

*Notes: Coefficient on wind can be interpreted as the effect of wind on the probability that ERCOT markets are congested, defined as an average price spread > 1 (38% of obs). Load is ERCOT-wide load. Fuelratio is average gas price/average coal price. Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Additional controls include linear and quadratic temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table B.3: Average marginal effect of wind generation - Matched sample

	(1)	(2)	(3)	(4)
	Total Dmg	Total Dmg	Total Dmg	Total Dmg
Wind	-53.05***	-52.97***	-53.62***	-52.79***
	(1.945)	(1.959)	(2.092)	(2.125)
Wind*Congested	13.29***	11.89***	8.414***	7.041***
	(2.331)	(2.170)	(2.443)	(2.390)
Congested	-137,929	-200,522	-208,458	-372,580
	(409,101)	(413,711)	(382,809)	(367,017)
Hour-Month FE	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y
All controls	Y	Y	Y	Y
Zonal load	Y	Y	Y	Y
Fully interacted	Y	Y	Y	Y
N	43,801	42,606	27,953	19,338
R^2	0.916	0.912	0.903	0.910

*Notes:Column (1) matches on wind generation and total load. Column (2) wind generation, total load and year. Column (3) matches on wind generation, individual loads from the West, South, North, and Houston zones, and year. Column (4) matches on wind generation, individual loads from the West, South, North, and Houston zones, year, and season. Hour-by-month, month-by-year, day of week fixed effects included. Control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table B.4: Average marginal effect of wind generation - alternative cutoffs

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) Total Dmg	(5) Total Dmg
Wind	-55.17***	-54.00***	-53.25***	-51.71***	-51.17***
	(2.376)	(2.053)	(1.941)	(1.908)	(1.933)
Wind*Congested	9.864***	11.07***	11.93***	13.04***	12.65***
	(2.366)	(2.320)	(2.188)	(2.315)	(2.543)
Congested	-36,558	-35,817	-93,051	-314,926	-330,430
	(378,699)	(401,590)	(386,682)	(408,017)	(407,759)
Congested cutoff	0	0.1	0.5	3	5
Hour-Month FE	Y	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y	Y
All controls	Y	Y	Y	Y	Y
Zonal load	Y	Y	Y	Y	Y
Fully interacted	Y	Y	Y	Y	Y
N	43,824	43,824	43,824	43,824	43,824
R^2	0.915	0.916	0.916	0.915	0.915

*Notes: Coefficient on wind can be interpreted as \$/MWh. Congested = 1 if average price spread exceeds noted cutoff. Percent of Congested hours across columns is 64.2%, 52.2%, 43.5%, 29.2% and 24.9% respectively. Hour-by-month, month-by-year, day of week fixed effects included. Control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table B.5: Average marginal effect of wind generation - zonal congestion defintion

	(1) Total Dmg	(2) Local Dmg	(3) CO_2 Dmg
Wind	-52.25***	-30.62***	-21.70***
	(1.893)	(1.716)	(0.407)
Wind*CongNorth	-3.195	-3.072	-0.156
	(2.890)	(2.624)	(0.479)
Wind*CongSouth	6.818***	5.817**	0.993*
	(2.433)	(2.203)	(0.502)
Wind*CongHouston	6.672***	6.159***	0.438
	(2.328)	(2.164)	(0.494)
CongNorth	4,722	7,924	-3,078
	(13,720)	(12,387)	(2,708)
CongSouth	-22,077	-15,431	-6,726**
	(13,231)	(11,910)	(2,699)
CongHouston	-30,585**	-30,587***	680.0
	(12,195)	(11,377)	(2,427)
Hour-Month FE	Y	Y	Y
Month-Year FE	Y	Y	Y
DOW FE	Y	Y	Y
All controls	Y	Y	Y
Zonal load	Y	Y	Y
Fully Interacted	Y	Y	Y
N	43,824	43,824	43,824
R^2	0.916	0.817	0.985

Notes: Coefficient on wind can be interpreted as \$/MWh. Cong = 1 if price spread exceeds \$1 for pairwise comparisons between ERCOT West and ERCOT North, South and Houston. Hour-by-month, month-by-year, day of week fixed effects included. Control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table B.6: Average marginal effect of wind generation - pairwise congestion definition

	(1)	(2)	(3)	(4)	(5)	(6)
	Total Dmg	Total Dmg	Total Dmg	Total Dmg	Total Dmg	Total Dmg
Wind	-52.55***	-51.47***	-52.37***	-50.67***	-51.74***	-51.85***
	(1.946)	(1.915)	(1.836)	(1.869)	(1.876)	(1.922)
Wind*Congested	10.84***	11.12***	12.48***	15.40***	12.65***	14.89***
	(2.263)	(2.756)	(2.363)	(3.157)	(2.489)	(2.417)
Congested	-473,457	-420,487	-21,673	-438,945	-564,006	-389,395
	(368,061)	(406,328)	(411,631)	(419,937)	(367,475)	(378,376)
Congested	W-S	W-N	W-H	N-H	N-S	H-S
Hour-Month FE	Y	Y	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y	Y	Y
All controls	Y	Y	Y	Y	Y	Y
Zonal load	Y	Y	Y	Y	Y	Y
Fully interacted	Y	Y	Y	Y	Y	Y
N	43,824	43,824	43,824	43,824	43,824	43,824
R-squared	0.916	0.915	0.916	0.915	0.916	0.916

*Notes: Coefficient on wind can be interpreted as $/MWh. Congested = 1 if price spread exceeds $1 between the noted regions (e.g. W-S is ERCOT West and ERCOT South). Hour-by-month, month-by-year, day of week fixed effects included. Control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table B.7: Average marginal effect of wind generation - donut congested

	OLS			
	(1)	(2)	(3)	(4)
Wind	-52.30***	-52.78***	-53.53***	-54.23***
	(1.871)	(1.958)	(2.090)	(2.313)
Wind*Congested	10.58***	11.10***	13.02***	11.76***
	(1.969)	(2.511)	(3.166)	(3.914)
Congested	-55,313***	-60,030***	-60,759***	-61,262***
	(9,000)	(10,711)	(12,742)	(14,906)
Donut	\$0.5-1.5	\$0.1-5	\$0.01-10	\$0.001-15
N	40,104	31,878	25,730	19,741
R^2	0.917	0.917	0.914	0.911

	IV-LASSO			
	(1)	(2)	(3)	(4)
Wind	-55.44***	-57.14***	-58.51***	-56.33***
	(3.172)	(3.025)	(2.961)	(2.708)
Wind*Congested	21.84**	31.11***	38.47***	21.69**
	(9.352)	(10.41)	(11.45)	(10.90)
Congested	-132,152**	-202,005***	-232,262***	-37,503
	(65,505)	(70,372)	(75,668)	(68,131)
Donut	\$0.5-1.5	\$0.1-5	\$0.01-10	\$0.001-15
Observations	40,103	31,877	25,729	19,740
R-squared	0.915	0.911	0.907	0.907

*Notes: Coefficient on wind can be interpreted as \$/MWh. Congested = 1 if average price spread is above the upper bound of the "Donut". Observations dropped if average price falls within the noted "Donut". Hour-by-month, month-by-year, day of week fixed effects included in all specification. Control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table B.8: Average marginal effect of wind generation - daily aggregation

	(1) Total Dmg	(2) Local Dmg	(3) CO_2 Dmg
Wind	-47.49***	-26.16***	-21.37***
	(3.608)	(3.258)	(0.798)
Wind*Congested	14.33***	11.89**	2.235**
	(5.165)	(4.658)	(0.941)
Congested	-9.644e+06	-1.036e+07	577,702
	(1.350e+07)	(1.188e+07)	(2.516e+06)
Month-Year FE	Y	Y	Y
DOW FE	Y	Y	Y
All controls	Y	Y	Y
Zonal load	Y	Y	Y
N	1,826	1,826	1,826
R^2	0.917	0.828	0.985

*Notes: Coefficient on wind can be interpreted as $/MWh. Congested is the average number of Congested hours in a given day. Month-by-year, day of week fixed effects included for all specifications. Control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table B.9: Data Summary - MISO

	Mean	SD	Min	Max
CO_2 damage ($)	1,681,668	315,859	904,414	2,898,647
SO_2 damage ($)	3,080,016	936,715	934,541	8,021,906
NO_X damage ($)	236,362	55,562	103,142	456,664
PM2.5 damage ($)	259,181	47,892	128,296	424,379
Zone 1 Congest Price ($)	-2.673	11.12	-307.7	238.3
Zone 2 Congest Price ($)	-0.889	8.995	-236.3	266.3
Zone 3 Congest Price ($)	-4.682	12.17	-303.2	160.9
Zone 4 Congest Price ($)	-0.958	8.099	-250.1	174.3
Zone 5 Congest Price ($)	-1.897	9.259	-302.6	164.4
Zone 6 Congest Price ($)	0.865	8.184	-216.4	230.7
Zone 7 (CONS) Congest Price ($)	2.028	14.00	-219.2	388.4
Zone 7 (DECO) Congest Price ($)	1.379	11.32	-265.6	274.5
Wind (MWh)	3,973	2,411	0	12,296
Congested	0.547	0.498	0	1
Total Load (MWh)	58,717	9,712	38,182	103,551
Fuel Price Ratio	0.0169	0.009	0.008	0.146

Notes: 2011-2015 MISO. 43,824 hourly observations in total. Zone 7 in Figure 6. Total Load is the summed load across the zones given in Figure 6.

Table B.10: Average marginal effect of wind generation on environmental damages - MISO with $c = 8$

	(1)	(2)	(3)	(4)	(5)
Wind	-61.96***	-80.92***	-81.50***	-82.94***	-83.12***
	(8.507)	(3.757)	(3.363)	(4.367)	(4.093)
Wind*Congested	-25.23***	10.69***	7.758***	7.053**	8.225**
	(8.753)	(2.898)	(2.702)	(3.458)	(3.145)
Congested	164,623***	-71,189***	-54,364***	-55,377***	-1.442e+06***
	(40,069)	(14,101)	(13,415)	(15,826)	(512,503)
Load		153.4***	135.1***		
		(11.70)	(11.19)		
$Load^2$		-0.000432***	-0.000308***		
		(8.77e-05)	(8.37e-05)		
Fuelratio		3.355e+07***	3.005e+07***	2.869e+07***	
		(1.015e+07)	(8.760e+06)	(1.008e+07)	
$Fuelratio^2$		-1.934e+08***	-1.740e+08***	-1.664e+08***	
		(5.701e+07)	(4.902e+07)	(5.830e+07)	
Add'l controls	N	N	Y	Y	Y
Zonal load	N	N	N	Y	Y
Fully interacted	N	N	N	N	Y
N	43,824	43,824	43,744	35,000	35,000
R^2	0.848	0.959	0.963	0.953	0.955

Notes: All specifications include hour-month, month-year, and day-of-week fixed effects. Coefficient on wind can be interpreted as $/MWh. Load is the northern MISO-wide load. Fuelratio is average gas price/average coal price. Additional controls include linear and quadratic temperature and MISO import/exports at important interfaces. Zonal load includes linear and quadratic controls for 8 MISO zones described in the text. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table B.11: Average marginal effect of wind generation on environmental damages - MISO with $c = 2$

	(1)	(2)	(3)	(4)	(5)
Wind	-47.68***	-83.79***	-81.75***	-83.60***	-87.82***
	(14.19)	(5.373)	(4.686)	(6.324)	(6.068)
Wind*Congested	-32.62**	9.030**	4.607	4.362	10.54**
	(12.40)	(4.000)	(3.456)	(4.721)	(4.735)
Congested	174,532***	-49,850***	-35,801**	-34,977**	-867,766
	(40,281)	(15,370)	(13,611)	(15,766)	(542,732)
Load		154.2***	135.7***		
		(11.60)	(11.14)		
$Load^2$		-0.000438***	-0.000313***		
		(8.67e-05)	(8.29e-05)		
Fuelratio		3.348e+07***	3.002e+07***	2.866e+07***	
		(1.016e+07)	(8.749e+06)	(1.007e+07)	
$Fuelratio^2$		-1.932e+08***	-1.739e+08***	-1.663e+08***	
		(5.716e+07)	(4.905e+07)	(5.834e+07)	
Add'l controls	N	N	Y	Y	Y
Zonal load	N	N	N	Y	Y
Fully interacted	N	N	N	N	Y
N	43,824	43,824	43,744	35,000	35,000
R^2	0.848	0.959	0.963	0.953	0.955

*Notes: All specifications include hour-month, month-year, and day-of-week fixed effects. Coefficient on wind can be interpreted as $/MWh. Load is the northern MISO-wide load. Fuelratio is average gas price/average coal price. Additional controls include linear and quadratic temperature and MISO import/exports at important interfaces. Zonal load includes linear and quadratic controls for 8 MISO zones described in the text. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table B.12: Event Study Summary Statistics

	Pre-Expansion			
	Mean	SD	Min	Max
Damages ($)	1,840,194	404,399	758,133	2,902,198
Wind (MWh)	3,774	2,326	8	9,542
Congested	0.476	0.499	0	1
$Load_{North}$ (MWh)	14,068	3,744	8,159	27,556
$Load_{South}$(MWh)	10,022	2,552	5,955	17,977
$Load_{West}$(MWh)	2,876	437	2,139	4,414
$Load_{Houst}$(MWh)	9,970	2,376	6,162	17,373
Fuel Price Ratio	0.016	0.002	0.012	0.020

	Post-Expansion			
	Mean	SD	Min	Max
Damages ($)	1,876,474	441,956	774,581	2,998,531
Wind (MWh)	4,098	2,574	14	10,844
Congested	0.297	0.457	0	1
$Load_{North}$(MWh)	14,517	3,602	8,399	25,955
$Load_{South}$(MWh)	10,562	2,645	5,972	18,168
$Load_{West}$(MWh)	3,364	447	2,530	4,781
$Load_{Houst}$(MWh)	10,396	2,313	6,625	17,772
Fuel Price Ratio	0.020	0.004	0.013	0.064

Notes: The "Pre-Expansion" sample covers hourly observations from 06/30/2012-06/30/2013 and the "Post-Expansion" sample is from 01/03/2014-01/03/2015.

Table B.13: Pre- vs Post-Expansion Estimates

	Pre	Post
Wind	-38.36***	-46.82***
	(3.353)	(2.495)
$Load_{Houst}$	34.48	47.58
	(53.41)	(39.65)
$Load^2_{Houst}$	-0.000410	-0.000291
	(0.00212)	(0.00159)
$Load_{North}$	125.9***	141.4***
	(30.33)	(24.39)
$Load^2_{North}$	-0.00252***	-0.00316***
	(0.000814)	(0.000699)
$Load_{South}$	55.07	88.77***
	(54.39)	(33.03)
$Load^2_{South}$	-0.000413	-0.00310**
	(0.00223)	(0.00126)
$Load_{West}$	-543.6	100.7
	(340.2)	(271.6)
$Load^2_{West}$	0.0740	-0.0144
	(0.0509)	(0.0374)
Constant	-411,797	-528,291
	(680,035)	(377,658)
Observations	8,784	8,784
R-squared	0.863	0.909

*Notes: The "Pre" sample covers hourly observations from 06/30/2012-06/30/2013 and the "Post" sample is from 01/03/2014-01/03/2015. Additional controls for each subsample include linear and quadratic values of Fuelratio, temperature, SPP load, and SPP wind. Hour-by-month and day of week fixed effects are included for each sub-sample. Cluster robust standard errors at day-of-sample are given in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

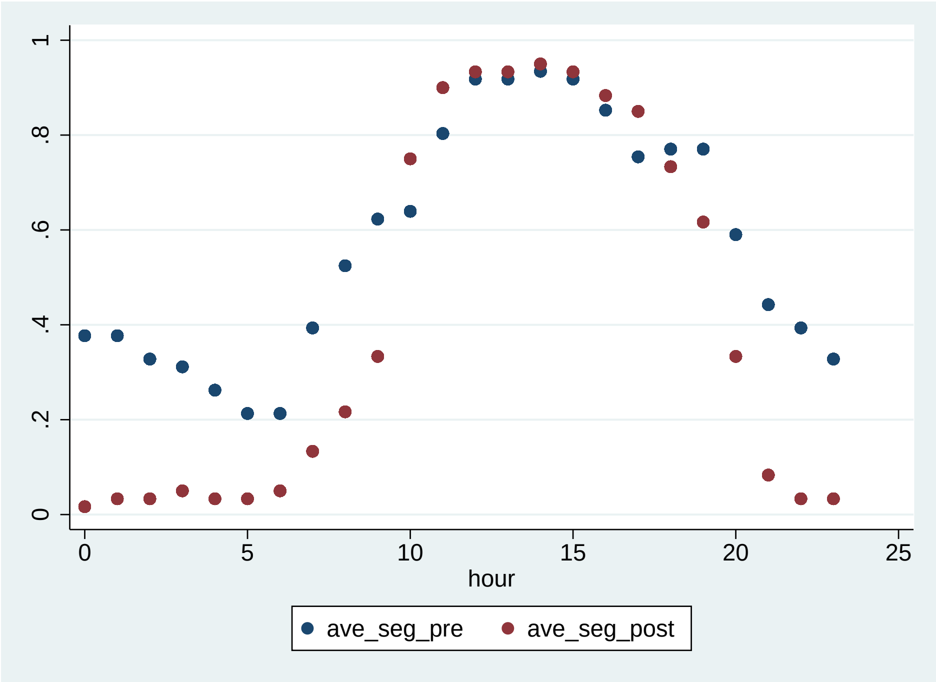

Figure B.1: Percent of hours that are congested in the two months pre- and post- major CREZ project completion on June 30, 2013.

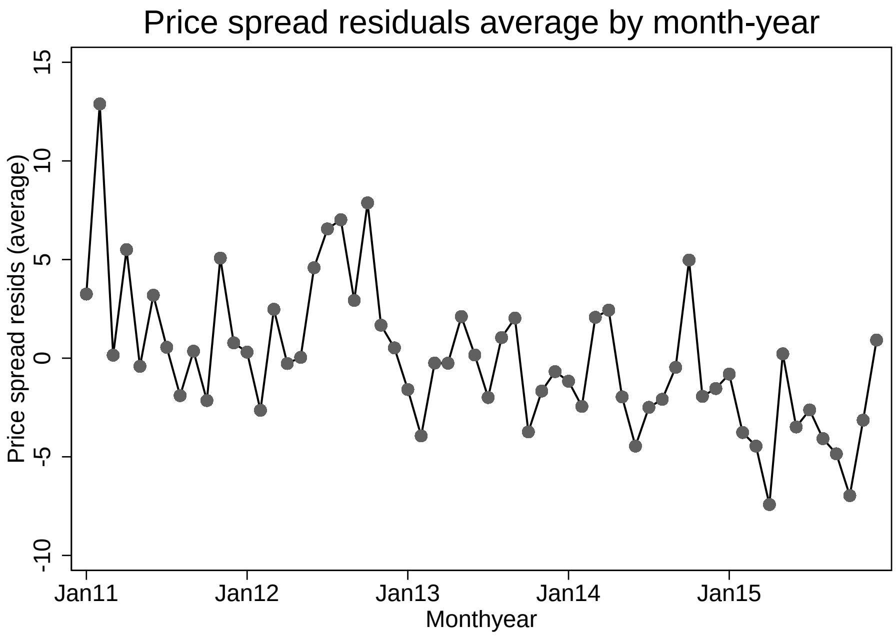

Figure B.2: Time series variation in average price spreads (demeaned by hour-month) in ERCOT.