Emissions, Transmission, and the Environmental Value of Wind Energy

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Abstract

Growth in renewable electricity generation has spurred substantial private and public interest in increasing transmission capacity to export electricity from renewable-rich, demand-poor regions to urban demand centers. While the primary motives for these transmission investments are market-based (e.g., arbitraging regional electricity prices), they can also have large non-market impacts (e.g., altering the level and location of pollution). In this paper, we examine how transmission congestion alters the environmental benefits provided by wind generation. Using hourly wind and emissions data from the Texas and Mid-Continent electricity markets, we find that relaxing transmission constraints between the wind-rich areas of the respective markets and the demand centers results in 33% and 13% increases in the non-market value of a MWh of wind for Texas and the Mid-Continent markets, respectively. Much of this increase in the non-market value arises from a redistribution in where emissions are avoided – in transmission unconstrained periods, wind offsets much more pollution from fossil fuel units located near highly populated demand centers.

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1 Introduction

A combination of state-level mandates, federal tax credits, and falling capital costs have driven a surge in U.S. renewable electricity capacity.[1] Utility-scale solar and wind farms, which produced less than 0.7% of total U.S. electricity in 2006, accounted for 7.6% of output in 2017. With ambitious renewable mandates in place in many states, the growth in renewables shows no signs of slowing.[2] However, much of this renewable capacity is concentrated in regions with high renewable energy potential (i.e. high and steady wind or high solar insolation) and often not near urban demand centers. A readily observable consequence of this siting pattern is that wholesale electricity prices in renewable-rich regions are often being driven below the prices observed in surrounding demand-rich regions due to electricity grid congestion, thereby reducing the *private* (market) value of renewables.[3] What is less obvious, but potentially of large economic significance, is how this electricity grid congestion affects the *social* (environmental) value of renewables. Congestion can impact the level of emissions avoided through renewable generation, as well as the location of pollutants avoided. This latter issue may be particularly important, given that region-specific damages associated with the release of certain pollutants are often considerably higher near urban demand centers (Muller and Mendelsohn 2009). In this paper, we address the issue

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[1] Capacity and generation data are available from the U.S. Energy Information Administration (EIA). From 2006 through 2015, utility-scale solar capacity increased from 0.8 gigawatts (GW) to over 27 GW and wind capacity grew from 22 GW to 145 GW. Schmalensee (2011) summarizes the renewable energy policies and Hitaj (2013) explores the policy impacts.

[2] Of the 76 GW of net capacity additions the EIA reports as planned for 2016 through 2020, almost half (37 GW) comes from solar and wind additions.

[3] The frequent occurrence of negative energy prices in renewable-rich regions like California and Texas due to grid congestion have garnered a great deal of attention 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`.

of how grid congestion affects the environmental benefits of renewable generation, particularly wind generation, in theoretical and empirical applications that explicitly consider the spatially-specific damages from local pollutants, as well as damages from global pollutants.

Consideration of the effect of grid congestion on the non-market value of renewables is currently of particular relevance as many electricity market system operators (independent system operators (ISO's) and regional transmission operators (RTO's)), utilities, and other private investors have pledged, or already spent, billions of dollars to expand and upgrade electricity transmission networks to accommodate renewable power generation. For example, from 2003 through 2012, California utilities spent $13 billion on transmission expansions, much of which went towards connecting Southern California demand centers to renewable-rich regions to the east.[4] Within the last decade, Texas utilities also completed multiple transmission upgrades at a cost of around $7 billion to help connect the windy western portion of the state with demand centers to the east. Similarly, the Mid-continent Independent System Operator (MISO), the grid management service for a large section of the middle of the U.S., approved the $6.6 billion Multi-Value Portfolio transmission project to in part provide greater access to the region's wind generation. Across the US, large utilities spent $21 billion on transmission infrastructure in 2016 alone.[5] Justifying such large expenditures on the grounds of private market benefits alone may often be difficult, so understanding how

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[4] Information on transmission investments is provided by the U.S. EIA, `https://www.eia.gov/todayinenergy/detail.php?id=17811`.

[5] As noted here, `https://www.eia.gov/todayinenergy/detail.php?id=3489https://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 this investment. Note also this value reflect only expenditures from large utilities that are required to fill out FERC form 1. This excludes non-utilities companies, which also spend considerable amounts on transmission. For example, a private firm, Clean Line Energy Partners, 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`).

congestion (or its alleviation through transmission capacity expansion) impacts non-market values of renewables will be key in determining if many of these projects are sensible.

Our analysis takes part in several steps. First, to first provide intuition for how transmission congestion affects the external benefits of renewable generation, we build on the transmission models of Joskow and Tirole (2005) and LaRiviere and Lu (2017) by incorporating global and local (region-specific) damages from pollutants. Differences in the environmental value of renewables in uncongested (i.e. no binding transmission constraint) and congested periods is dictated by two channels. First, by relaxing a transmission constraint between regions, output from renewables can offset production from a different set of conventional generators with potentially different emission rates (e.g. coal versus gas), thereby affecting the *levels* of emissions offset. Second, relaxing transmission constraints also alters the*location* of emissions offset. In the case of local pollutants, this 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)).

Next, in an empirical application, we quantify how the environmental benefits of wind generation are affected by congestion. Specifically, using observed hourly wind generation, we estimate how a marginal increase in wind generation affects the hourly external damages across a given market footprint when the electricity system is congested and when it is not.[6] Importantly, when creating our system-wide environmental damage variable, we explicitly account for both global emissions (CO_2), as well as the levels and location of local pollutants

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[6] We exploit region-specific hourly electricity prices in defining our "congested" market periods, whereby congested hours are generally defined as those such that the renewable rich regions and the surrounding regions function as separate regional markets, each with their own market clearing prices.

(SO_2, NO_x, and PM2.5) and their associated county-specific damages. We estimate this relationship between market-region environmental damages and wind generation under congested and uncongested system conditions across many different cuts of the data, including at different times of the day, across different years, under varying definitions of "congested", and different regional definitions of environmental damage.

Geographically, our empirical analysis focuses on data from the Electricity Reliability Corporation of Texas (ERCOT) market, which covers the majority of Texas, and the MISO market region. These two market regions are well suited for this investigation as they have the highest wind generation of all the ISO/RTO regions in the U.S. In addition, similar to the US more generally and several other nations expanding their renewable energy capacity, much of the wind generation in these two market areas is concentrated in the less-populated, portions of the market footprints.[7] For example, the vast majority of Texas' 20-plus gigawatts (GW) of wind capacity have been installed in the wind-rich, sparsely populated northwest portion of the state (see Figure 1). In contrast, the major demand centers (e.g., Houston, Dallas, Austin, San Antonio) are located further east. Given this spatial distribution of wind and power demand, in 2008, the Public Utility Commission of Texas (PUCT) designated five regions in northwest Texas as Competitive Renewable Energy Zones (CREZs) and laid out plans to dramatically increase transmission capacity between these wind-rich CREZs and urban demand centers to the east, approving over $7 billion in spending on transmission capacity upgrades and expansions from 2009 through 2015. The project has had a major impact on wholesale electricity prices. Prior to 2012, hourly prices in renewable-rich West

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[7] For example, China, which is currently investing more in renewable energy than any other nation, also 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).

Texas regularly fell below the market clearing prices in the North, South, and Houston regions (see Figure 2 for map of ERCOT zones). By 2015, prices were far more uniform across the four regions. We exploit this transmission project in several ways in our empirical analysis.

Our results reveal several very robust patterns. First, our results clearly indicate, across a variety of specifications and in both regions examined, that grid congestion reduces the marginal environmental value of wind generation. Specifically, our base results indicate that system congestion reduces the environmental value of an additional megawatt-hour (MWh) of wind generation in ERCOT by about 25 percent (around \$53/MWh in uncongested periods and \$40/MWh in congested) and by about 12 percent in MISO (from \$85/MWh to \$75/MWh). Second, we find that for both regions, the lost environmental value of wind generation is driven by local instead of global pollutants. That is, 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). By contrast, the marginal value of wind generation in terms of CO_2 reductions is much less affected by congestion (marginal values are reduced by 8 and 7 percents, respectively, across ERCOT and MISO). This result supports the intuition that congestion inhibits the ability of renewable generation dispatched from less-populated regions to reduce generation from sources emitting local pollutants in high-damage urban areas. Third, by replacing our county-specific emission damage estimates with region-wide average damage estimates, we show that the marginal value of wind generation in uncongested periods declines and that the lost environmental value of wind generation in congested hours is also reduced. This again highlights the importance of considering spatial heterogeneity of environmental damages in considering both the environmental value of wind and how it is altered by transmission constraints.

We also use our parameter estimates from ERCOT to estimate a back-of-the-envelope external value of the CREZ transmission expansion project. Specifically, by assessing the reduced frequency of system congestion attributable to the completion of the CREZ expansion combined with our estimates of the lost external value of wind during congested period, we estimate that the CREZ expansion increased the external value of ERCOT wind generation by approximately $100 million per year. Finally, we exploit CREZ expansion construction dates to conduct an event study to look for evidence that the established relationship between the environmental value of wind and system transmission constraints holds in the opposite direction as well - is the environmental value of a transmission capacity expansion greater in a system with more wind generation? Though not a perfect empirical setting, comparisons of predicted environmental damages at different wind levels based on model estimates from data just prior to and directly following a relatively short window of considerable transmission expansion are consistent with a complementary relationship between wind generation and transmission capacity. While CREZ expansion has no environmental benefits at low levels of wind generation, at high levels of wind generation, the post-expansion system has considerably lower predicted environmental damages than the pre-expansion system.

Our analysis is novel in several ways. First, rather than focusing solely on the CO_2 avoidance benefits of renewable energy as others have (e.g. Callaway et al. (2018), Fell and Kaffine (2018)), we consider the environmental value of wind generation with respect to both global and local pollutant damages. Second, though others have also considered the value of wind generation in avoiding local pollutants (e.g. Cullen (2013), Kaffine et al. (2013), Novan (2015)), we more explicitly account for the region specific damages created by these emissions, and thus our marginal value of wind generation is driven by not only what type of pollutants wind generation reduces but also where those emissions are reduced. Finally, to our knowledge, this is the first econometric study that assesses the role transmission constraints play in determining the external value of wind generation. In our analysis this turns out to be quite important as congestion alters which fossil-fuel generators renewables offset and thus alters the levels and spatial pattern of pollution.

The remainder of this paper proceeds as follows. Section 2 presents a simple model providing intuition for how transmission constraints and market congestion can affect the non-market value of renewable electricity. Section 3 summarizes the data and empirical strategy used to evaluate the impact of wind generation on emissions. Section 4 presents the estimates of the non-market value of wind generation with and without binding transmission constraints. Section 5 discusses the implications of the empirical results and Section 6 concludes.

2 Transmission and environmental damages offset by wind

To provide some intuition on how transmission can affect the non-market value of wind generation, consider an extension of the transmission models in Joskow and Tirole (2005) and LaRiviere and Lu (2017) to include wind generation, emissions, and environmental damages. Note, the purpose of this section is not provide an exhaustive examination of all theoretical issues related to transmission, wind generation, and environmental damages, but rather to motivate some useful insights for the empirical analysis to follow.

Suppose there are two regions, West and East, where West represents a wind-rich region that produces W wind generation at zero marginal cost. Absent transmission constraints, the East would purchase electricity from the West until prices equilibrate $p_w = p_e$ and the markets are uncongested (single price). Let $MC_w(F_w)$ represent the marginal cost of a given level of fossil generation F_w in the West, and similarly $MC_e(F_e)$ in the East. Then given power demand levels, often refered to as "load" and reasonably assumed to be perfectly inelastic over short time-spans, L_w and L_e and quantity Q of exported electricity from the West,[8] $F_w = L_w - W + Q$ and $F_e = L_e - Q$, then:

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

Given an increase in wind, exported electricity from the west Q will increase per: $\frac{dQ}{dW} = \frac{MC'_w}{MC'_e + MC'_w}$, with the magnitude depending on the relative slopes of the regional marginal cost curves. Similarly, $\frac{dF_w}{dW} = -\frac{MC'_e}{MC'_e + MC'_w}$ and $\frac{dF_e}{dW} = -\frac{MC'_w}{MC'_e + MC'_w}$, and the market price will fall.

Consider emissions associated with fossil generation in the above model, where we distinguish between global pollutants (CO_2) and local pollutants such as SO_2, NO_x, PM2.5. Global pollutant production in each region is given by $g_i(F_i) > 0$ for $i = w, e$ and $g'_i > 0$, and similarly for local pollutants $s_i(F_i) > 0$ for $i = w, e$ and $s'_i > 0$. Next, let γ_g represent the (common) dollar damages per unit of global pollutants, while δ_w and δe represent local damages from local pollutants in the West and East. Total environmental damages can then be expressed as:

$$D(W) = \gamma_g(g_w(F_w(W)) + g_e(F_e(W))) + \delta_w s_w(F_w(W)) + \delta_e s_e(F_e(W)). \tag{2}$$

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[8] Load can be thought of as net of baseload nuclear and other renewables such as hydro or solar.

Differentiating with respect to wind W yields the following expression for how wind affects environmental damages in an uncongested market:

$$\frac{dD}{dW} = -\gamma_g\left(g'_w \frac{MC'_e}{MC'_e + MC'_w} + g'_e \frac{MC'_w}{MC'_e + MC'_w}\right) - \delta_w s'_w \frac{MC'_e}{MC'_e + MC'_w} - \delta_e s'_e \frac{MC'_w}{MC'_e + MC'_w}. \tag{3}$$

which expresses the change in environmental damages in terms of the marginal emission rates in each region, g'_i and s'_i evaluated at the equilibrium level of fossil generation in each region, (e.g. $g'_w(F_w)$), and the marginal damages per unit of pollution, γ_g and δ_i. Importantly, because markets are uncongested, an additional unit of wind generation can offset fossil generation in either the West or the East.

However, given a transmission constraint (congestion) between West and East, prices in the West will be depressed relative to the East due to zero marginal cost wind power. Let $\bar{K}$ represent the level of transmission capacity required to fully export the desired quantity of electricity out of the West. Then if actual transmission capacity K is less than $\bar{K}$, $p_e = p_w + \eta(K)$, where $\eta(K)$ is the shadow cost of the transmission constraint, such that $\eta(K) > 0$, $\frac{d\eta}{dK} < 0$, and $Q^c = K$ when $K < \bar{K}$. Putting this together, we have that:

$$MC_e(L_e - Q^c) = MC_w(L_w - W + Q^c) + \eta(K). \tag{4}$$

This establishes the following relationships due to an increase in wind generation if the transmission constraint is binding and markets are congested: $\frac{dQ^c}{dW} = 0$, $\frac{dF^c_e}{dW} = 0$, and $\frac{dF^c_w}{dW} = -1$. Intuitively, if transmission is congested, then an increase in wind can only offset fossil generation in the West. As such, differentiating Equation 2 with respect to wind when markets are congested yields the following:

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

While inspection of Equations 3 and 5 reveals the important distinction that wind in congested markets will only offset West fossil, while wind in uncongested markets can offset fossil generation anywhere, direct comparison is complicated by the fact that the emissions functions in the West are evaluated at different levels of fossil generation (F_w vs F_w^c). If we make the (strong) assumption that marginal emission rates are the same (locally), $g_w'(F_w) = g_w'(F_w^c)$ and $s_w'(F_w) = s_w'(F_w^c)$, then the difference in environmental damages offset by wind in uncongested versus congested markets is:

$$\frac{dD}{dW} - \frac{dD^c}{dW} = [\gamma_g(g_w' - g_e') + (\delta_w s_w' - \delta_e s_e')] \frac{MC_w'}{MC_e' + MC_w'}. \tag{6}$$

Wind will be more environmentally valuable in uncongested markets if the above expression is negative, which will be more likely if marginal generation in the East is dirtier than in the West, and/or if local pollutant damages are larger in the East.

To further explore this result, suppose that $\delta_e = \delta(1+\nu)$ and $\delta_w = \delta$, such that damages from local pollutants in the East are larger ($\nu > 0$) or smaller ($\nu < 0$) than in the West. Then from above we have:

$$\frac{dD}{dW} - \frac{dD^c}{dW} = \underbrace{[\gamma_g(g_w' - g_e') + \delta(s_w' - s_e')] \frac{MC_w'}{MC_e' + MC_w'}}_{\text{Emissions Level Effect}} - \underbrace{\delta\nu s_e' \frac{MC_w'}{MC_e' + MC_w'}}_{\text{Emissions Location Effect}}. \tag{7}$$

where 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 pollutant generation in the East, which may have different local marginal damages. Clearly, if local marginal damages are much higher in the East, then total environmental damages offset by wind can be larger via the *Location Effect*, with the net effect depending on the sign and magnitude of the *Level Effect*.[9]

Applying the above insights to our empirical analysis to follow, we expect that when transmission is constrained and market prices across regions differ due to congestion, a marginal unit of wind will tend to offset generation near wind facilities primarily located in the renewable rich regions. By contrast, when transmission is not constrained (i.e. the market is uncongested), a marginal unit of wind may offset generation in other parts of the given market region. Per the above, when the market is uncongested, the *Emissions Level Effect* might suggest that wind is less likely to offset coal generation in renewable region, lowering its environmental value. On the other hand, if there are more coal plants outside of the renewable region that can respond to wind when markets are uncongested, then the *Emissions Level Effect* may increase the environmental value of wind. By contrast, the *Emissions Location Effect* most certainly increases the environmental value of wind and may be quite large due to (much) higher population densities (e.g Figure 3 vs 4) and thus higher marginal damages from local pollutants outside of the renewable rich regions.

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[9] 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 7: $\gamma_g \alpha_g + \delta_w \alpha_w$. This term, a *Supply-curve effect*, captures movement along the fossil supply curve in the West due to congestion constraints, reflecting the emissions rate of the particular fossil generator offset by an additional unit of wind. In practice, the emissions functions g_i and s_i may be very globally non-linear with non-monotonic first derivatives, so the sign of the above 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 in the section to follow. To demonstrate that our analysis is more broadly applicable, we then apply a similar analysis to the MISO region, as described in Section 5 below.

3.1 Data

We collect various market, generation, and weather data from the ERCOT and MISO regions. In this section, we discuss the data collected for ERCOT in detail. The data for our analysis of MISO is similarly structured and will be discussed briefly in section 5.

Our analysis uses hourly observations from 2011-2015 in ERCOT. 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).[10] We collect hourly generation and emission data from each generating unit as reported through the EPA's Air Markets Program Data (AMPD) database.[11] In addition, we collect locational information, specifically the county in which the plant is located, given in the EIA 860 data. 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).[12] Taking

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[10] Capacities by generation type across the four ERCOT load zones for 2011 are shown in Figure 5 and for 2015 in Figure 6.

[11] 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 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.

[12] 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

all this together, in every hour h, for each emissions type p and plant i located in county c which emits f_{ipc}, we calculate damages as:

$$D_{hdmy} = \sum_i \sum_p s_{pc} * f_{ipc}, \tag{8}$$

where s_{pc} is the dollar damages per unit of emissions type p in county c. While s_{pc} is constant across all counties for CO_2 emissions, for the local pollutants SO_2, NO_X, and PM2.5, s_{pc} can vary substantially across counties.[13] D_{hdmy} is thus ERCOT-wide environmental damages for hour h, day d, month m and year y. In our analysis below, we also disaggregate this total damage value into global damages (CO_2) and local damages (SO_2, NO_X, and PM2.5). We further spatially decompose the ERCOT-wide damages, such that we form ERCOT load zone-specific damages to assess mechanisms by which transmission constraints and market integration affect the environmental value of wind.

We regress these measures of environmental damages on ERCOT wind, various other controls for market conditions, and measures of market congestion. Hourly wind generation for ERCOT is obtained from ERCOT. We also control for levels of hourly electricity demand by including the measure of "load" (electricity consumed) at the the ERCOT-wide level and at the load-zone level.[14] 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

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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.

[13] 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. This is given in 2011 dollars, as are the county-specific damages.

[14] 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.

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.

We take several complementary approaches to classifying whether or not the market is congested in a given 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).[15] A more challenging classification issue is when there are differences in zonal prices that are "small." Our base specification begins by calculating the average of the 6 pairwise differences in hourly electricity prices across the ERCOT load zones West, North, South, and Houston:

$$Spread_{hdmy} = \frac{|P_{i,hdmy} - P_{j,hdmy}|}{6} \tag{9}$$

This value 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

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[15] 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.

takes the value of 1 when the average price spread exceeds some cutoff value c. Formally,

$$C_{hdmy} = 1(Spread_{hdmy} > c), \tag{10}$$

where c is set to \$1 in our base specification. In alternative specifications discussed below, we examine different cutoff values of 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 yields results that are qualitatively, and often quantitatively, similar to results shown below.

Summary statistics for ERCOT are reported in Table 1. Figure 7 displays the average number of congested hours for each month of the sample, showing a substantial drop-off in congested hours in the later post-CREZ expansion years (based on ERCOT documentation, the bulk of CREZ is completed around mid-to-late 2013 - see Appendix A). Variation in the average price spread over time (demeaned by hour-by-month fixed effects) is also shown in Figure 8. In Figure 9, we regress hourly damages in each zone against fossil fuel generation in each zone, including hour-by-month and month-by-hour fixed effects, to obtain a sense of the zone-specific hourly damages from fossil fuel generation. 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.

3.2 Empirical strategy

Our base regression specification takes the following form:

$$D_{hdmy} = \alpha + \beta_1 W_{hdmy} + \beta_2 W_{hdmy} C_{hdmy} + \beta_3 C_{hdmy} + \sum_i \theta_i^j f_i(X_{hdmy}) + \gamma_{hm} + \eta_{my} + \delta_d + \epsilon_{hdmy}, \tag{11}$$

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 wind generation in MWh, and C_{hdmy}, which is an indicator for whether the market was congested. The term X_{hdmy} is a set of control variables for total ERCOT load and the fuel price ratio between gas and coal, which enter flexibly (typically as a quadratic). The remainder of the terms represent fixed effect controls 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 (diurnal variation) that may be correlated with changes in the shape or composition of the load profile. Similarly, month-by-year fixed effects η_{my} will control for longer-run trends such as increasing wind capacity and changes in the 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, unless otherwise noted, 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.

4 Results

In this section, we report estimates from the regression model described above. We begin by discussing our results pertaining to our basic specification that estimates the environmental value of wind in uncongested versus congested market conditions, followed by a series of robustness checks. Next, we examine the underlying mechanisms and channels (e.g. Emissions Level and Emissions Location Effects per the above) that drive the differences between the environmental value of wind in different market conditions. We then examine heterogenous effects in the environmental value of wind across different years, seasons, and hours. Finally, we employ an instrumental variable approach, leveraging the CREZ expansion in part, to further support our interpretations of key results.

4.1 Environmental value of wind

Estimation results of variants on equation 11 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 $Wind * Congested$ corresponds to β_2, and these can be readily interpreted as the average dollar change in environmental damages due to a marginal change in wind generation (MWh) 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 Table 2, which adds linear and quadratic controls for total ERCOT load and fuel price ratios.[16] Column 3 Table 2 adds linear and quadratic controls for average Texas temperatures, and wind generation and load in the neighboring Southwest Power Pool (SPP) market region, with key coefficients essentially unchanged.[17] Column 4 Table 2 replaces total ERCOT load with linear and quadratic controls for load in each of the four ERCOT zones, while Column 5 Table 2 fully interacts all controls and fixed effects from Column 4 Table 2 with *Congested*.

Taking Column 5 Table 2 as the preferred specification, during uncongested market conditions a MWh of wind generation offsets around \$53 dollars in environmental damages. By contrast, in congested conditions wind has lower environmental value, approximately \$13/MWh dollars less than in uncongested hours. This corresponds to an environmental value of wind in congested periods of \$40/MWh in contrast to the \$53/MWh in uncongested periods - in other words, wind is 32% more environmentally valuable when markets are uncongested.

To determine if this lower environmental value during congested hours is driven by local versus global pollutants, in Columns 1 and 2 of Table 3, 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. These estimates reveal the difference in environmental value in congested versus uncongested periods is primarily driven by changes in local pollutant

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[16] 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)).

[17] 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`.

damages - of the \$13/MWh difference in total damages, \$11/MWh can be attributed to local damages versus \$2/MWh from CO2. Per Section 2, recall there are two primary channels, the Emissions Level Effect and the Emissions Location Effect, by which an uncongested market can affect the environmental damages offset by wind.[18] The small benefit associated with more CO_2 emissions offset during uncongested hours, indicates the composition of the generators that respond to wind is different during uncongested periods (relatively more coal offset during uncongested hours).

To more closely look at this issue, we next consider cases where we remove the spatial variation in damages from local pollutants. This should isolate the Emissions Level Effect, as a unit of emissions has the same environmental damages, regardless of where it was emitted. Column 3 and 4 of Table 3 replaces the spatially-explicit damages from local pollutants with the mean or median damages, respectively, across all counties with a fossil generator. Ignoring the spatial aspects of local damages 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 as well (roughly half). This suggests that of the \$11 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).[19]

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[18] Intuitively, the Emissions Level Effect is about *what* type of generation is offset by wind (e.g. coal vs gas combined cycle vs gas turbines), while the Emissions Location Effect is about *where* those generators are located.

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

All together, the above results make a strong case that uncongested markets increase the environmental 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. By contrast, when markets are uncongested, wind is more environmentally valuable as wind power in ERCOT West can offset dirtier fossil generation in populated areas, particularly in Houston where the marginal damages from fossil generation are very large (Figure 9). We look more closely at this interpretation below.

4.2 Robustness checks

Next, we consider a series of exercises to explore the robustness of the above results to alternative assumptions and specifications. First, the base specification classifies congested market conditions as hours where the average price spread across zones was greater than \$1 dollar. While this cutoff is somewhat arbitrary, we can examine whether varying this cutoff dramatically affects the estimated environmental value of wind. Note there is likely classification error tradeoffs in either direction of the cutoff - 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.2 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.

In addition to varying the cutoff, we also examine alternative ways of defining the *Congested* variable in equation 11. First, Appendix Table B.3 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.4 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, in order to more cleanly distinguish congested and non-congested hours, Appendix Table B.5 drops observations when differences in zonal price are greater than zero but "small", yielding similar estimates to those above.

As a final robustness exercise, we look at two issues related to the dynamic properties of the data. First, results above cluster at the month-year level to capture within-month serial correlation. To the extent this may be overly conservative, Appendix Table B.6 reports standard errors from clustering at the weekly and at the daily level, as well as simple robust standard errors. As expected, these yield tighter parameter estimates. Second, our model assumes solely contemporaneous effects between wind and environmental damages; however, 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 intraday spillovers between hours, Appendix Table B.7 aggregates to the daily level, yielding estimates of environmental damages avoided that are very similar to the hourly estimates.

4.3 Mechanisms

Having established robust results above, we next look more closely at our interpretation of these estimates. 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 4 examines total environmental damages by zone as the dependent variable, and estimates are consistent with the above story. Focusing on the coefficient on $Wind * Congested$, it is positive and economically and statistically significant for ERCOT Houston, implying smaller environmental benefits in ERCOT Houston when markets are congested. By contrast, for ERCOT West, the interaction coefficient is negative and significant, implying larger environmental benefits in ERCOT West from wind when markets are congested. So while congestion leads to less reductions in ERCOT Houston and more reductions in ERCOT West, the fact there are substantially more people affected by fossil generators in ERCOT Houston results in a net reduction in environmental damages in congested hours.[20]

While the above results focus on zonal damages, we can drill down even further to the specific coal plants in Figures 3 and 4. W.A. Parish coal plant (four units, total 2.7 GW capacity) is located in the Houston suburbs (metro pop 6.7 million), while Oklaunion coal plant (single unit, 720 MW capacity) in Wilbarger County ('metro' pop 13,000) is the sole coal plant in ERCOT West. Table 5 estimates generation and environmental damage responses to wind in uncongested and congested periods at these two plants, yielding estimates

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[20] 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.

consistent with the story above. Specifically, Oklaunion is twice as responsive to wind in congested hours when transmission constraints force a local ERCOT West fossil response to wind generation, while W.A. Parish is half as responsive to wind in congested hours as 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 the predominant story is that congestion often arises due to the fact that 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, the fact remains that 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.[21] Table 6 reports the results from this estimation. Consistent with our hypothesis

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[21] While on average the relative frequency of negative and positive congestion are roughly equal, this does

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 negatively and positively congested hours despite reflecting very different states of the market.

4.4 Heterogeneous effects

To further explore the environmental value of wind in congested versus uncongested market conditions, we next examine the heterogeneity of this value 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 perhaps some omitted variable bias was unduly influencing our findings. In Table 7, 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 \$12 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 increase emissions, this would positively bias the $Wind * Congested$ coefficient, exaggerating the diminished environmental value of wind in congested market conditions.[22] Scheduled

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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.

[22] 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

maintenance typically occurs during the "shoulder" months outside of the winter and summer peak load months. In Table 8, 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 $Wind * Congested$ is actually larger in non-shoulder months, though not statistically distinguishable ($p = 0.143$ for total damages). This suggests that, to the extent there is a possible bias on $Wind * Congested$ from plant outages, it is towards zero, and our base results may be slightly understating the diminished environmental value of wind in congested market conditions. We return to issues related to this in the next section.

Finally, because different fossil units are marginal during different hours of the day, as load changes throughout the day, the environmental value of wind will also likely vary by hour of day. Figure 10 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

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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.

magnitude.

4.5 Total effects and exogeneity of the *Congested* variable

As a final set of considerations, we next examine two important questions related to the *Congested* variable. First, given that wind affects the probability that ERCOT markets are congested, and congested markets may lead to different environmental outcomes independent of wind generation, are there large environmental effects through this channel? Second, once we control for wind generation and zonal loads, what is the remaining variation in Congested and is it exogenous?

Consider a model of emission damages conceptually similar to Equation 11 that explicitly recognizes that congestion depends on wind generation:

$$D(W) = \beta_1 W + \beta_2 W * C(W) + \beta_3 C(W). \tag{12}$$

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

$$\frac{dD}{dW} = (\beta_1 + \beta_2 C(W)) + (\beta_2 W + \beta_3)\frac{dC}{dW}. \tag{13}$$

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

To gain a sense of the empirical magnitude of this indirect effect, Appendix Table B.8 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 the effect of $Wind$ on *Congested* is our coefficient of interest - across specifications, this coefficient is remarkable consistent.[23] 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.8, 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. Given that this is an order of magnitude or two smaller than the main effects, our focus in the analysis on the main, direct effect of wind on environmental damages is reasonable.

Next, we examine the exogeneity of the *Congested* variable. From Appendix Table B.8, even after controlling for zonal loads, wind levels, and a host of other controls and fixed effects, substantial variation in the *Congested* variable remains.[24] While this is helpful from the perspective of sufficient identifying variation, it does raise the question - is this remaining variation exogenous?

To address the exogeneity of the *Congested* variable, we adopt an instrumental variable approach to instrument for C_{hdmy} and $W_{hdmy}C_{hdmy}$ in Equation 11. Specifically, we require instrumental variables Z_{hdmy} that affect whether or not markets are congested, but do not (conditionally) affect environmental damages. Examination of ERCOT documents and other engineering sources suggest that a) weather conditions and b) transmission capacity (such as the CREZ expansion) are important determinants of congestion which are plausibly condi-

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

[24] One concern may be that the hours that are congested are significantly different in terms of the level of load and wind generation than hours that are uncongested. Inspection reveals that there is a surprising amount of overlap in load and wind levels for congested and uncongested hours. Appendix Table B.9 examines this more formally using a coarsened exact matching algorithm to match across several dimensions. Across specifications, we continue to find that wind generation in congested hours does not reduce damages as much as it does during uncongested hours.

tionally exogenous.[25] Thus, we construct instruments Z_{hdmy} and $W_{hdmy}Z_{hdmy}$ where Z_{hdmy} is a vector that includes weather variables for Texas average wind speed, wind direction, and cloud cover, a CREZ completion variable that captures the percentage of the CREZ project completed, and an interaction of the previous variables with total ERCOT load.[26]

Table 9 reports results from this instrumental variable regression. While the estimated environmental damages offset during uncongested hours are similar to the OLS estimates, the interaction coefficient on $Wind{*}Congested$ from the IV estimation is substantially larger than in the OLS estimation. While some of the increase in magnitude may be attributable to the LATE aspects of the IV estimation (for example, if the probability of congestion in off-peak hours responds most frequently to the instruments), the IV estimates suggest that our OLS estimates of the decline in the environmental value of wind due to congestion are, if anything, conservative.

5 MISO Results

The MISO market region covers a large swath of the middle of the US (see Figure 11) and has the most wind generation (in total MWh's) of any ISO/RTO in the U.S. MISO also has relatively concentrated renewable (wind) generation capacity that is positioned relatively far

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[25] The ampacity of a transmission line, a measure of the maximum current that the line can carry, is affected by, among other factors, ambient weather conditions of temperature, wind speed and direction, and solar radiation (see https://cleanenergygrid.org/transmission-technology-series/ for more details). Lower ampacity will increase the likelihood of transmission congestion. We therefore use Texas average wind speed, wind direction, and cloud cover as instruments for *Congested*.

[26] The CREZ completion variable is the share of miles of CREZ-related transmissions line completed, where "completed" is determined as the date the line was energized. Specific line energizing dates were provided by ERCOT. The interaction with load is driven by the observation that the change in the probability of congestion likely depends on total system load. For example, Appendix Figure B.1 examines the share of congested hours for two months before and after a major CREZ line was completed on June 30, 2013. During high load, mid-day hours, markets remain congested at roughly the same frequency, but during lower load, off-peak hours, the frequency of congestion drops considerably after the line completion.

from major demand centers. More specifically, much of the region's wind generation capacity is located in Iowa, southern Minnesota, and other more westerly areas of the MISO region and far from several key demand centers in the east portion of the market region (see Figure 12). Indeed, as can be seen in Figure 13, wind generation from the western states covered in MISO (IA, MN, MT, ND, and SD) account for about 75% to 90% of MISO's total wind generation over the months included in our study period.

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 less. As with ERCOT, the environmental value of wind generation is likely reduced during periods of market congestion. To assess this assertion, we conduct a similar analysis to the one above on data from MISO. The "total damage" dependent variable for MISO is formed in the same way as it was for ERCOT; multiplying generating-unit emissions by county-specific damages and summing over all generating units in MISO.[27] We exclude the south region of MISO (AR, LA, MS, TX) as that region was added in the middle of our sample period of 2011-2015. Hourly wind generation for all of MISO was accessed through MISO's website (www.misoenergy.org) on their "Market Report Archives" page. Zonal prices and load are quoted for the northern portion of MISO based on the zones depicted in Figure 14.[28] Note

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[27] 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.

[28] 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.

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 create zonal gas-to-coal fuel price ratios in the same manner as described above for the ERCOT zones. Summary statistics for the MISO region data are given in Appendix Table B.10.

The formation of the congestion dummy is done slightly differently for our MISO analysis given how the prices are quoted there. 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:

$$C_{hdmy} = 1(congest_{min,hdmy} < -c \quad \text{OR} \quad congest_{max,hdmy} > c) \tag{14}$$

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.[29]

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[29] 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.

Parameter estimates from regressions that are MISO-specific variations of Equation 11 are given in Table 10. As expected, these 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 results where load and other controls are included indicating that the marginal value of wind falls by about 8-13 percent in congested hours. The results also indicate that wind generation is in general more environmentally valuable in MISO compared to ERCOT. This is again as expected given that MISO has considerably more coal-fired generation than ERCOT. Also similar to the ERCOT results, in comparing the local versus CO_2 damages (see Table 11), we see that congestion has a much larger effect on damages from local pollutants. We also similarly find that if one assesses the role of congestion on the environmental value of wind by using a region-wide average (or median) estimates for per-unit damages from local pollutants, the impacts of congestion are much smaller and in this case statistically insignificant. This again highlights the need to consider spatially explicit damage estimates when considering the interaction of renewable generation and transmission congestion.[30]

6 Implications and additional considerations

To put the above results into perspective, this section first examines the impacts of transmission expansion on the environmental value of wind. During the time period of our sample,

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[30] Beyond the results shown here, we also considered specifications with higher and lower cutoff values for the determination of a congested hour (Appendix Tables B.11 and B.12). 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.

ERCOT built out transmission capacity to ERCOT West (CREZ lines) with the explicit goal of increasing the ability of wind generated in the West to get to the load centers in the east.[31] While this clearly has important market impacts on prices (LaRiviere and Lu 2017), the above analysis suggests this expansion also may have had important non-market consequences as well. How much more environmentally valuable is wind given this CREZ transmission expansion?

While it is clear that the probability that markets were congested declined from pre-CREZ to post-CREZ years, causally measuring its effect is challenging given the staggered rollout of energization of CREZ lines (Figure 15). Nonetheless, to get an order of magnitude, back-of-the-envelope estimate, we first compare the unconditional segmentation 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 segmentation of 24.3 percentage points. Using the coefficient estimates in Table 2, average hourly wind generation of 3825.3 MWh, and the change in the probability of segmentation suggests a roughly $100 million dollar annual increase in the environmental value of wind due to increased market integration. To check if this is simply a result of changes in load or fuel prices, we also examined the residual congested values after controlling for (quadratic) load and fuel prices, as well as month-by-year and day-of-week fixed effects. This conditional decline in segmentation from 2011-2012 to 2014-2015 is slightly larger at 28.4 percentage points, giving a roughly $120 million dollar annual increase in the environmental value of wind due to increased market integration. Note that of this roughly $100 million dollar increase in environmental value, the bulk of it comes from decreased damages from local

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[31] See additional discussion of the CREZ expansion in Appendix A.

pollutants, per the above results.

Finally, the results for ERCOT and MISO clearly show that the environmental value of wind increases when congestion is reduced, which one would expect to happen with increased transmission capacity from renewable heavy regions to demand centers. That is, renewable energy and transmission capacity have a complementary aspect. It also stands to reason that the environmental value of transmission capacity itself is greater with more renewables on the system.[32] As 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, about 60% of the transmission project was completed in the last half of 2013 (see Figure 15).[33] This relatively short window of substantial transmission expansion gives us an opportunity to run an event study (of sorts) where we can compare predicted environmental damages at different levels of wind generation using observations before the large jump in transmission to those predictions based on observations after the jump. Specifically, in our simplest specifications we estimate the following equation separately on data from the pre- and post-jump samples:

$$D_{hdmy} = \beta_0 + \beta_1 W_{hdmy} + \sum_i \theta_i^j f_i(X_{hdmy}) + \gamma_{hm} + \delta_d + \epsilon_{hdmy} \tag{15}$$

where $f_i(X_{hdmy})$ is again a function of control variables that include linear and quadratic specifications of zonal load, load and wind from SPP, and average temperature. We also again include hour-by-month (γ_{hm}) and day-of-week (δ_d) fixed effects. We define the pre-

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[32] This falls from the simple theory model presented above. 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 not always the case in ERCOT or other regions.

[33] Figure 15 plots the share of CREZ completed based on miles of line completed. We consider a segment of line completed as the date the line was energized according to project update data provided to us by ERCOT.

jump sample as the year 06/30/2012 - 06/30/2013 and the post-jump sample as the period 01/03/2014-01/03/2015. These two sample periods are shown as the shaded regions in Figure 15 and, as can be seen, exclude the approximately six-month period where CREZ progresses from about 40% completed to 100%. 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%.

After estimating the parameters in (15) for each sample separately, we then make separate predictions of the environmental damage based on the pre- and post-jump sample estimates over a range of wind generation values.[34] The prediction results from this exercise are given in Figure 16. The figure displays the predicted total damages (and the 95% confidence intervals) at different assumed wind generation levels based on estimates from the pre- and post-jump samples. As with the other empirical approaches presented, the figure again depicts a complementary relationship between transmission and renewables with respect to environmental damages. In this particular case, 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, which generally increases environmental damages. Conversely when wind generation is high, generation flows will generally be from west to east, and increased transmission flow will facilitate more substitution from high-

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[34] Summary statistics and point estimates on each sample are reported in Appendix Table B.13 and B.14For the remaining controls in 15, the prediction of environmental damages are made with these variables at their respective mean values over the two samples combined.

damage fossil fuel in the east with lower-damage fossil fuel in the west or even with wind generation itself in the west.[35] Accordingly, we find that the environmental damages are predicted to be noticeably lower with high wind in the post-jump period than in the earlier pre-jump period.[36]

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 from renewable rich and demand poor areas to population centers (e.g. from the Great Plains to the east in the US). While such projects are usually advocated on the grounds of market considerations such as arbitraging regional electricity prices or grid reliability, in this paper we examine how transmission and market integration affect the non-market/environemental value of wind power. ERCOT and MISO are useful locations to examine this issue, as they are in some sense a 'microcosm' of the US as a whole, with a wind-resource rich but demand poor area in the west, and larger population centers in the east.[37]

Theoretically, we highlight that there are two channels by which transmission expansions or constraints can affect the non-market value of wind. First, transmission congestion alters

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[35] 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.

[36] Beyond simple linear specifications, we also considered specifications where wind enters 15 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.

[37] China faces a similar situation of substantial wind resources in the low population north and west and has several large transmission lines built or under construction to move electricity to coastal load centers in the east.

which marginal fossil units respond to wind generation, affecting emissions and damages via a Emissions Level Effect - e.g. shifting from gas to coal, or vice versa, as the marginal unit. Second, transmission can also change where marginal fossil units respond to wind, affecting emission damages via a Emissions Location Effect - e.g. shifting responding fossil units from low population areas to high population areas. Combining 2011-2015 hourly data on wind generation and emissions with county-level damages by pollutant, we find that during hours when the ERCOT market was congested, wind energy provided \$40 per MWh in environmental benefits from avoided emission damages. By contrast, during hours when the ERCOT market was uncongested (common price across all zones), wind energy provided \$53 per MWh in environmental benefits, a 33% increase in the non-market value of wind. The bulk of this increased value in uncongested periods comes from reductions in local pollutants, driven primarily by shifting fossil response from ERCOT West to coal plants in ERCOT Houston. Examination of the CREZ transmission expansion project in ERCOT suggests non-market benefits on the order of \$100 million annually, similar in magnitude to the market benefits found in LaRiviere and Lu (2017). A similar pattern emerges in MISO as well, where grid congestion reduces the environmental value of wind, as wind generation in western MISO areas such as Iowa and southern Minnesota is unable to reach demand centers in eastern MISO.

Future research in this area could extend this analysis to other electricity markets in the US such as PJM, SPP, or WECC where transmission line expansions are planned. While we find that transmission expansions and more uncongested markets in ERCOT and MISO increased the environmental value of wind, it is unclear if that is true of other regions with different fuel mixes and spatial distributions of wind resources and emission damages.

Additional analysis could also be conducted on the CREZ transmission expansion specifically, to provide a deeper understanding of how transmission line expansions affected spatial prices and environmental values.

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Table 1: Data Summary - ERCOT

	Mean	SD	Min	Max
CO_2 damage ($)	797,561	226,314	255,341	1,544,803
SO_2 damage ($)	909,958	263,343	168,715	1,575,828
NO_X damage ($)	51,066	17,428	12,764	132,068
PM2.5 damage ($)	94,961	26,655	25,963	163,362
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 ($)	32.00	80.02	-9.93	4,515.98
Houston RTM Price ($)	32.63	82.60	-21.27	4,371.74
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	0.0163	0.0043	0.0071	0.0641

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

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

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) Total Dmg	(5) Total Dmg
Wind	-52.27***	-50.94***	-53.39***	-52.39***	-52.93***
	(3.348)	(1.670)	(1.951)	(1.872)	(1.932)
Wind*Congested	9.621***	12.85***	12.35***	10.37***	13.13***
	(2.990)	(2.180)	(2.037)	(1.844)	(2.344)
Congested	-108.8	-66,292***	-62,741***	-53,812***	-225,656
	(15,721)	(9,855)	(9,458)	(8,709)	(399,744)
Load		73.10***	72.36***		
		(5.045)	(5.639)		
Load^2		-0.000429***	-0.000382***		
		(5.66e-05)	(6.58e-05)		
Fuelratio		3.660e+07**	3.899e+07**	3.995e+07**	
		(1.588e+07)	(1.524e+07)	(1.515e+07)	
Fuelratio^2		-5.322e+08**	-5.369e+08***	-5.379e+08***	
		(2.039e+08)	(1.928e+08)	(1.906e+08)	
Hour-Month FE	Y	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y	Y
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	0.814	0.908	0.910	0.913	0.916

*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 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 3: Average marginal effect of wind generation - local vs global

	(1) Local Dmg	(2) CO_2 Dmg	(3) Local Dmg (average)	(4) Local Dmg (median)
Wind	-31.13***	-21.87***	-23.31***	-17.45***
	(1.731)	(0.426)	(1.280)	(0.932)
Wind*Congested	11.23***	1.774***	7.519***	5.408***
	(2.090)	(0.464)	(1.657)	(1.210)
Congested	-149,910	-76,415	-241,107	-179,280
	(355,178)	(62,007)	(212,965)	(154,672)
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	0.817	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 state-wide average and state-wide 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, 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 4: 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)
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	0.731	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 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 5: 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
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

*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 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 6: 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)
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	0.818	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 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 NegCongested and PosCongested variables. Cluster robust standard errors at month-by-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 7: 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)
Hour-Month 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	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, 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 week-of-year in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table 8: 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
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

*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. 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 9: Average marginal effect of wind generation - IV estimates

	(1) Total Dmg	(2) Local Dmg	(3) CO_2 Dmg
Wind	-59.72***	-36.66***	-23.02***
	(3.021)	(2.642)	(0.759)
Wind*Congested	42.11***	35.13***	6.464***
	(8.149)	(6.802)	(1.864)
Congested	-307,144***	-254,778***	-48,932***
	(59,209)	(49,091)	(12,710)
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
Kleibergen-Paap rk Wald F stat	15.075	15.075	15.075
N	43,726	43,726	43,726
R^2	0.543	0.253	0.902

*Notes: First-stage 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. 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 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 10: 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 11: 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)
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	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. Zonal load includes linear and quadratic controls for the 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*

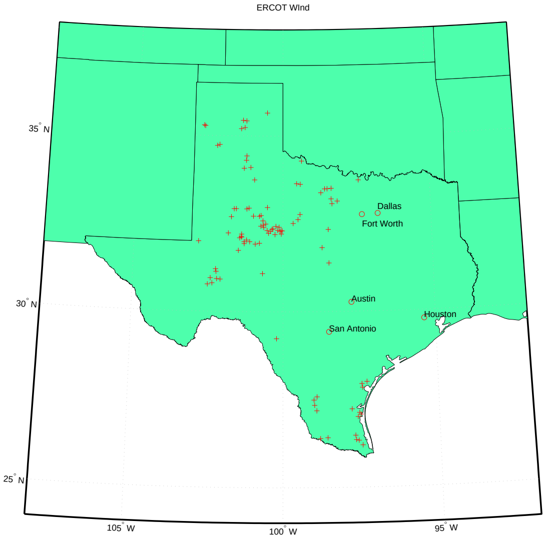

Figure 1: Location of wind farms in Texas (source: EIA 860 Form)

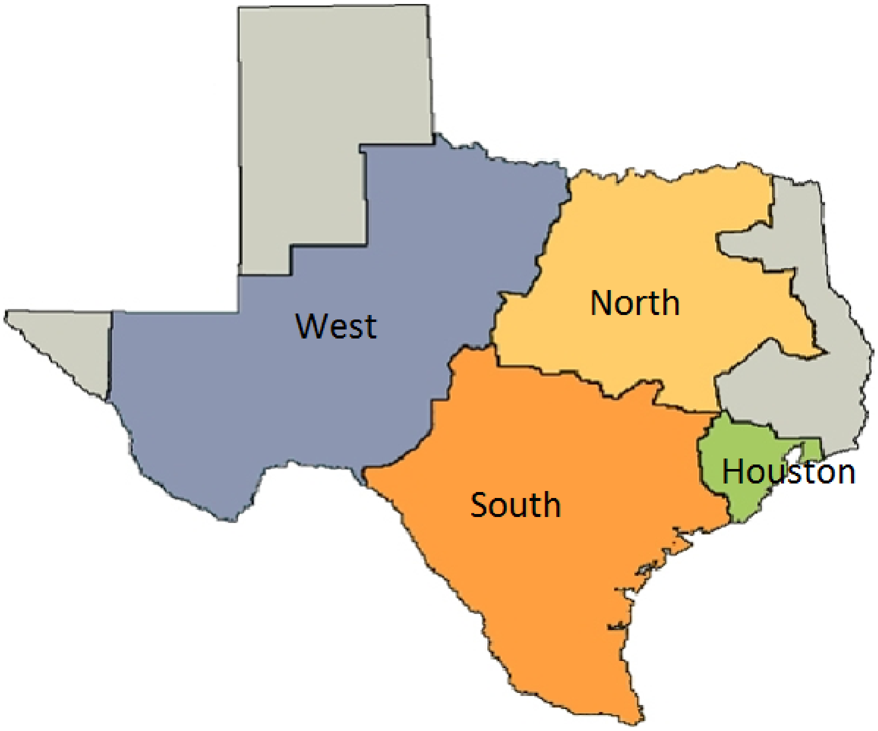

Figure 2: ERCOT zones (source: ERCOT)

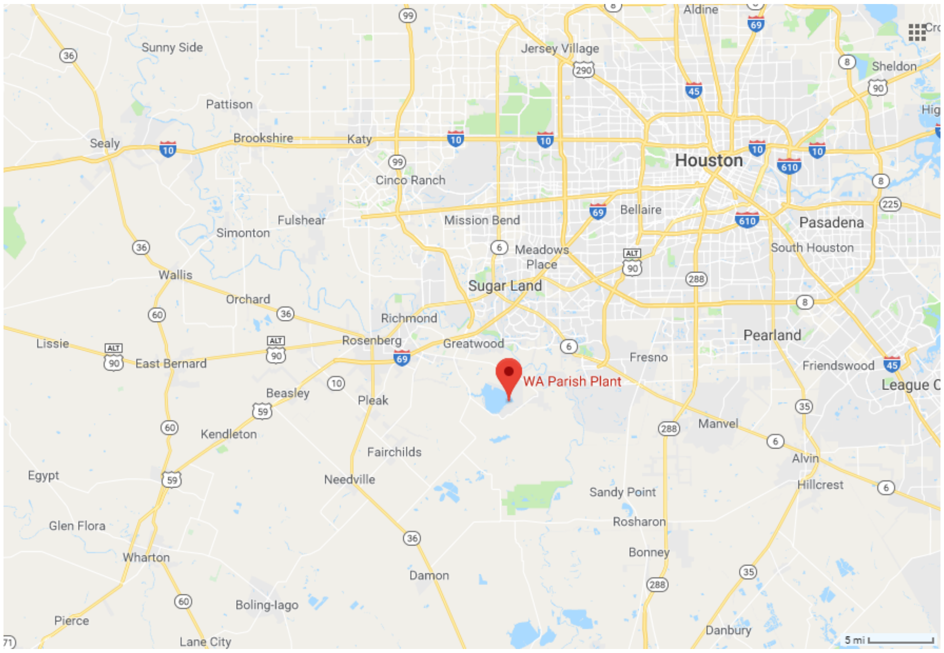

Figure 3: W A Parish coal plant in Fort Bend County near Houston (ERCOT Houston Zone)

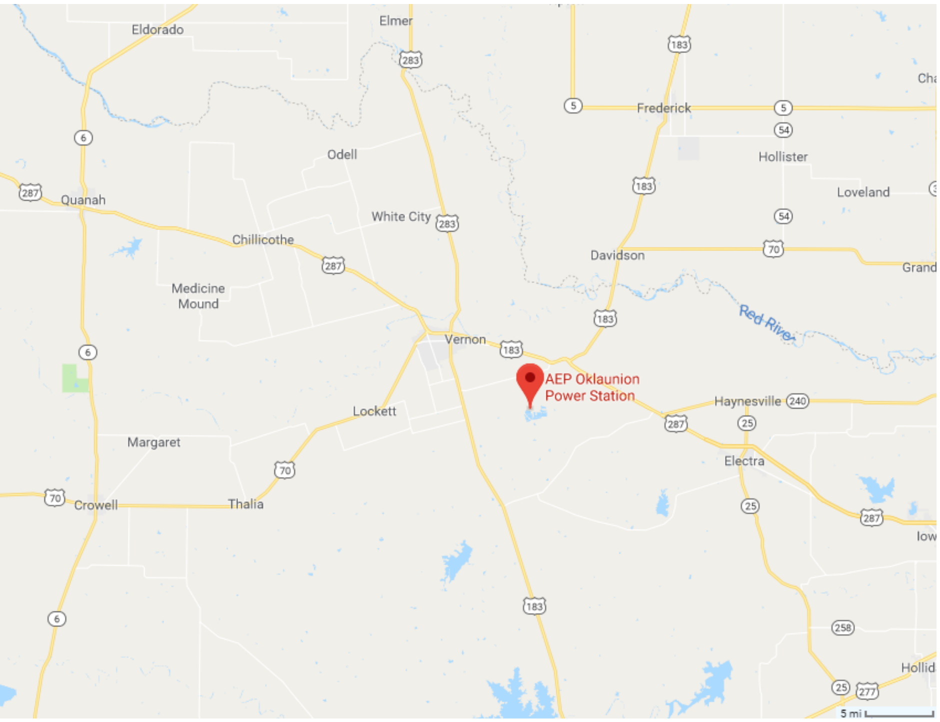

Figure 4: Oklaunion coal plant in Wilbarger county roughly 200 miles WNW of Dallas (ERCOT West Zone)

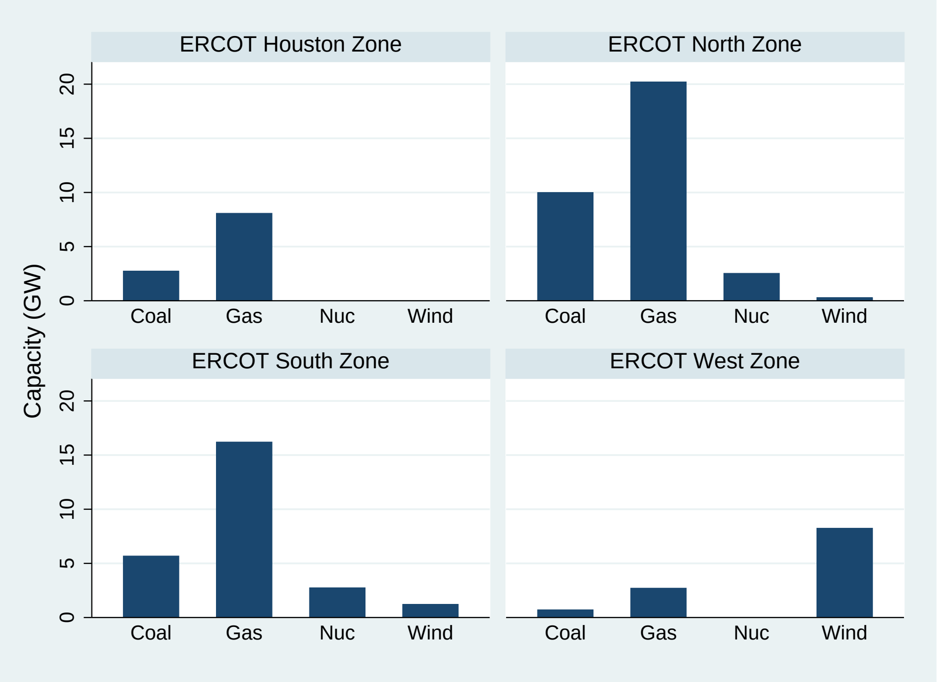

Figure 5: 2011 Capacities by zone for ERCOT (source: EIA 860 Form)

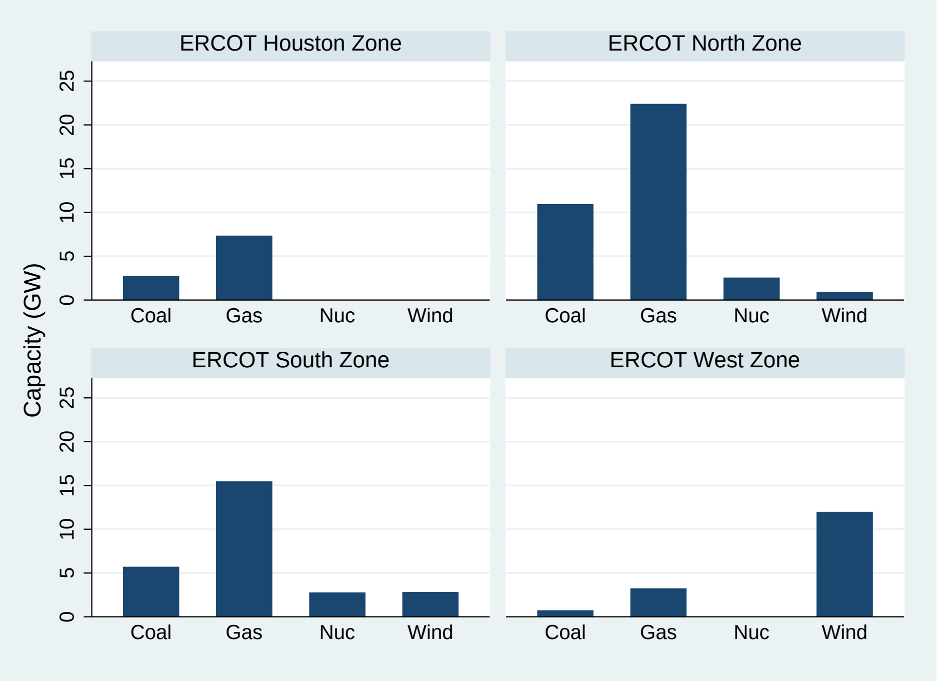

Figure 6: 2015 Capacities by zone for ERCOT (source: EIA 860 Form)

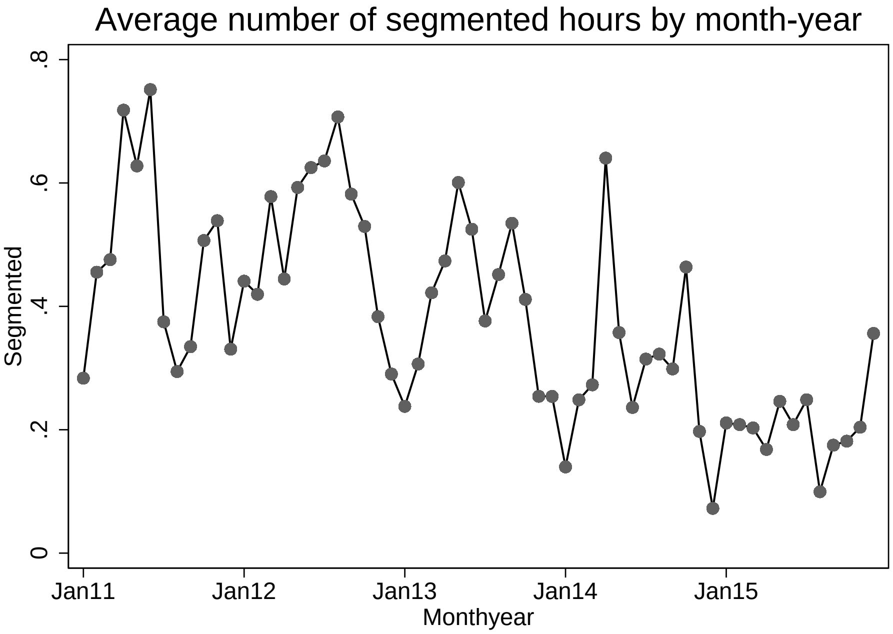

Figure 7: Time series variation in Congested hours in ERCOT.

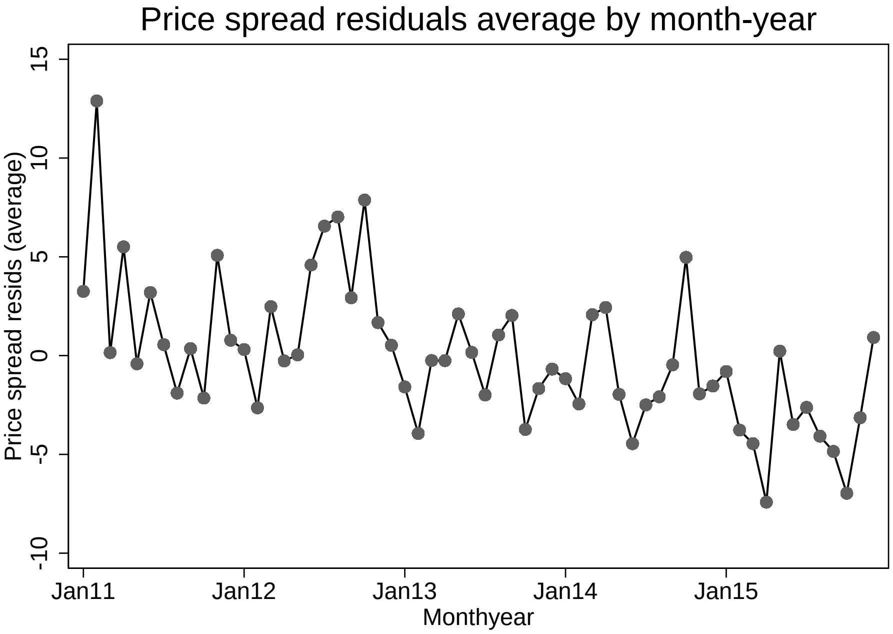

Figure 8: Time series variation in average price spreads (demeaned by hour-month) in ERCOT.

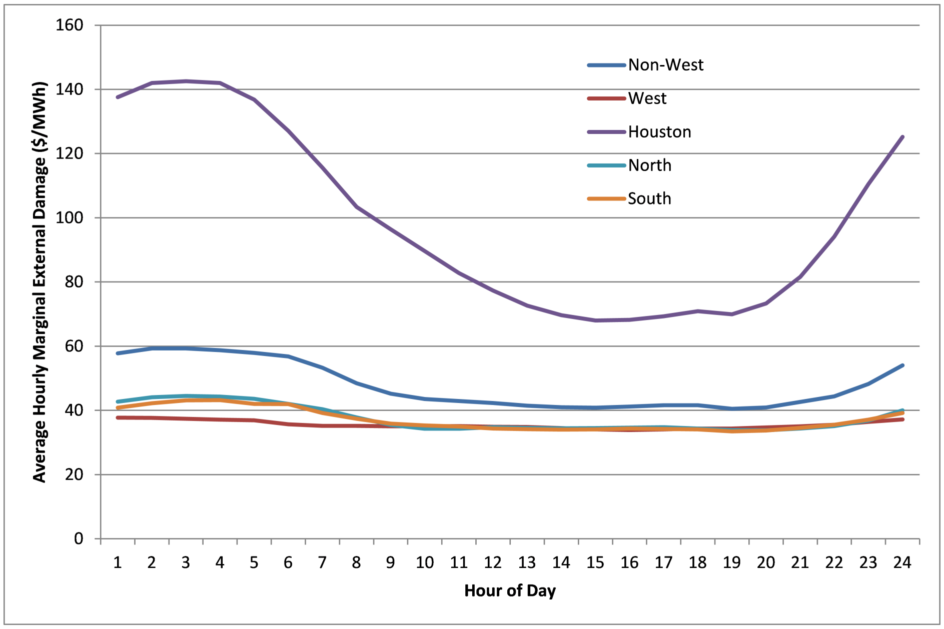

Figure 9: Damages from MWh of fossil generation across ERCOT zones.

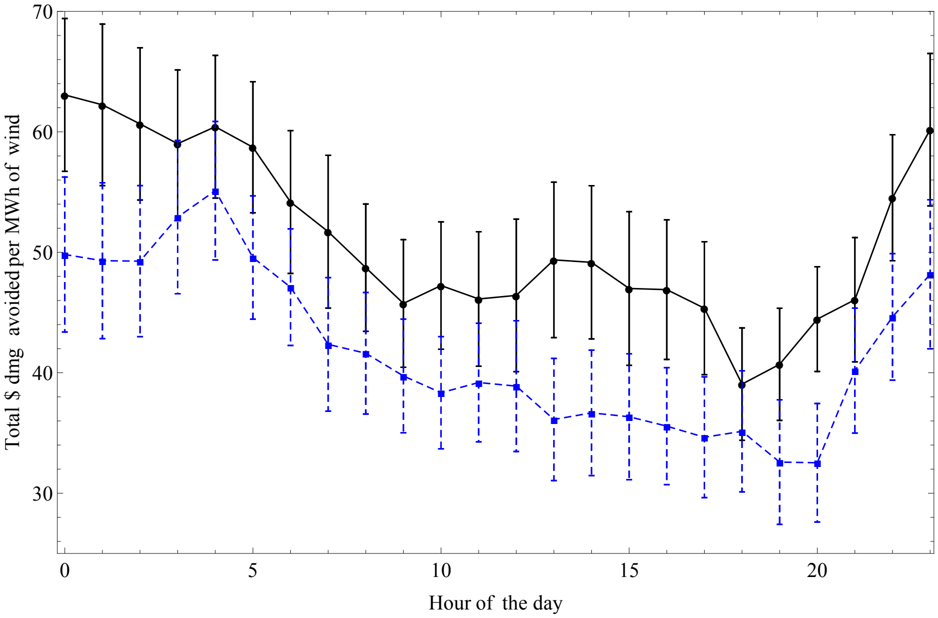

Figure 10: Environmental value of wind by hour in Uncongested (solid) and Congested periods (dashed) in ERCOT.

Figure 11: MISO Market Region (source: MISO)

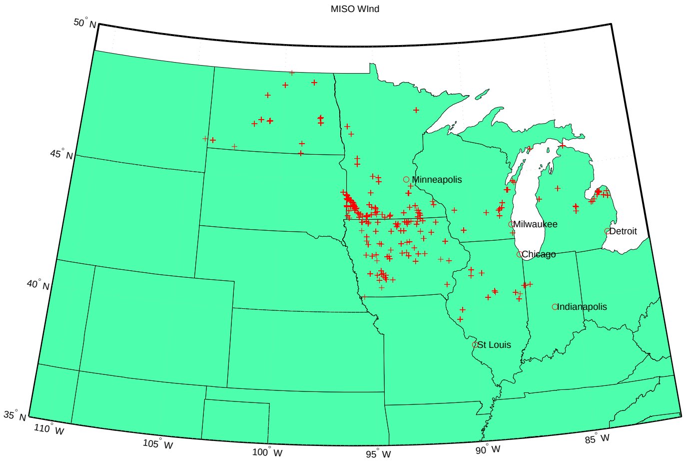

Figure 12: Wind Farms in MISO (source: EIA 860 Form)

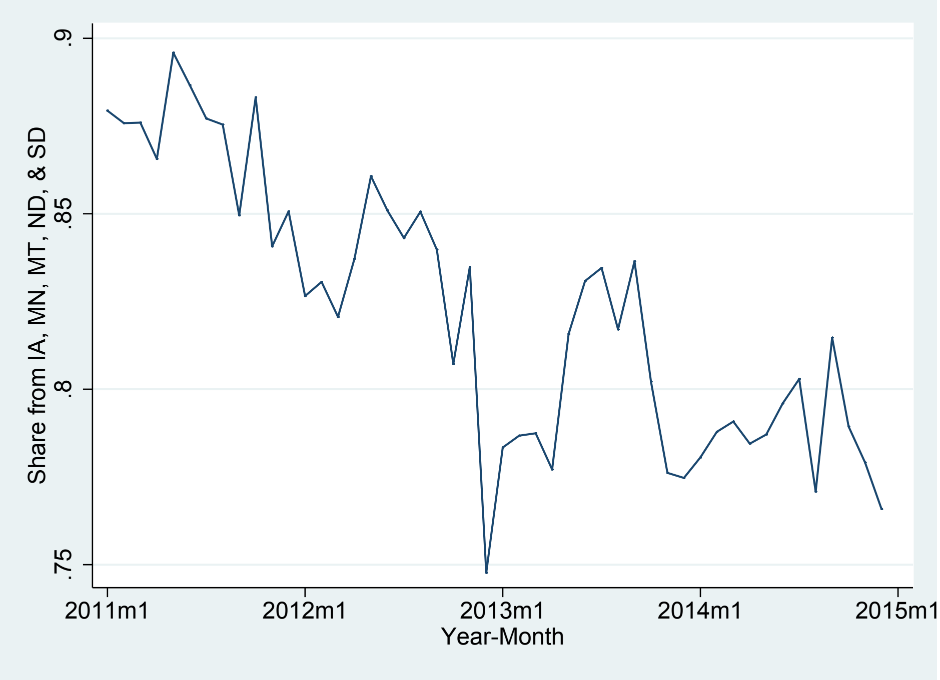

Figure 13: Share of Total MISO Wind from Its Western States (source: EIA 923 Form)

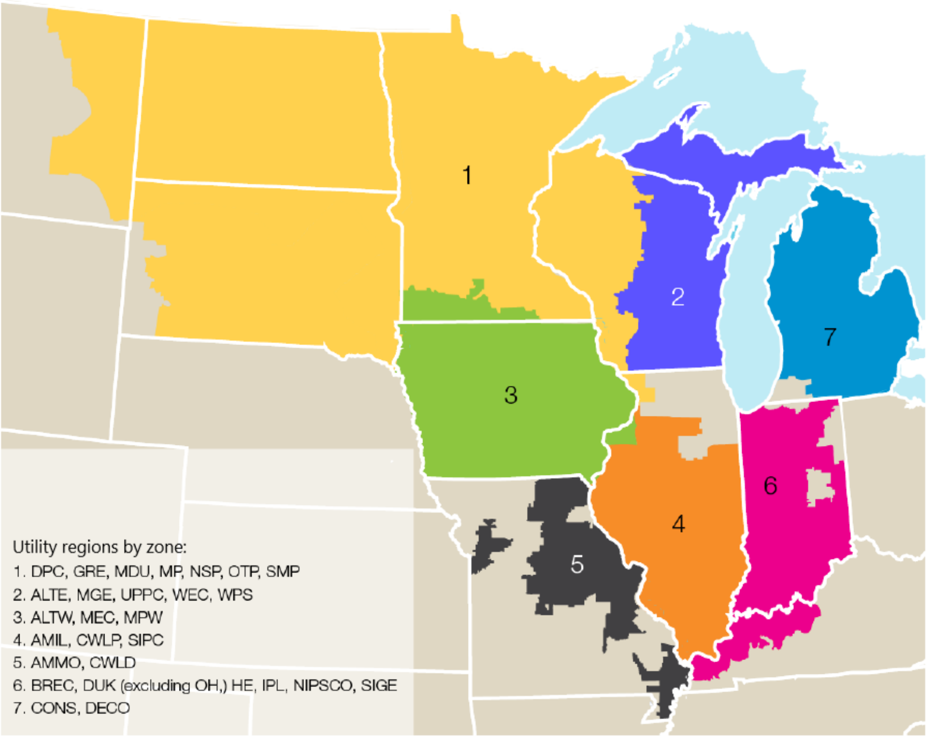

Figure 14: MISO Zones (source: MISO)

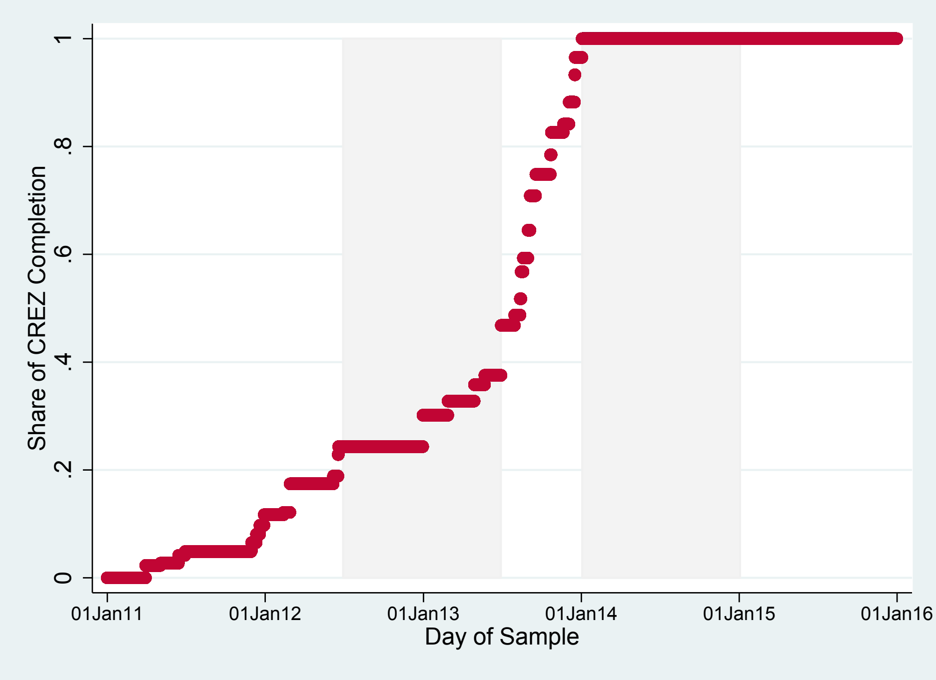

Figure 15: Share of CREZ completion with shaded pre-/post-CREZ jump samples (source: ERCOT)

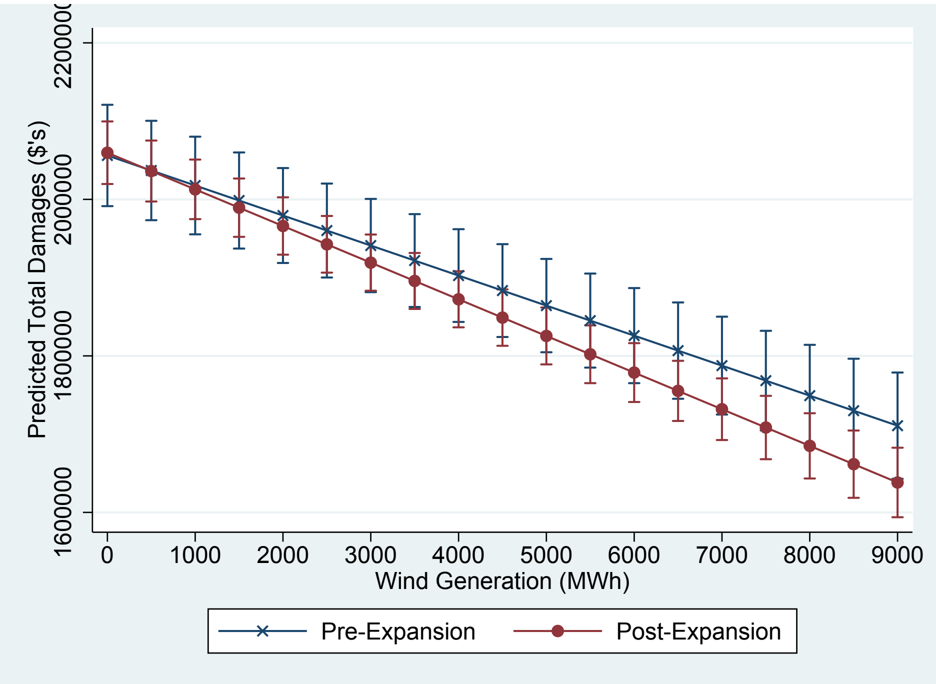

Figure 16: Predicted environmental damages in the pre-/post-CREZ jump samples versus varying levels of wind generation.

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) SO_2 (lbs)	(2) NO_x (lbs)	(3) PM2.5 (lbs)	(4) 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 - 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.3: 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.4: Average marginal effect of wind generation - pairwise congestion definition

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) Total Dmg	(5) Total Dmg	(6) 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.5: Average marginal effect of wind generation - donut congested

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) Total Dmg
Wind	-53.25***	-54.00***	-54.67***	-55.17***
	(1.943)	(2.059)	(2.222)	(2.400)
Wind*Congested	13.76***	15.48***	18.79***	22.93***
	(2.418)	(2.947)	(3.471)	(4.310)
Congested	-512,767	-518,094	-585,097	-541,905
	(410,393)	(430,478)	(447,023)	(436,412)
Donut	\$0.5-1.5	\$0.1-5	\$0.01-10	\$0.001-15
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	40,104	31,878	25,730	19,741
R^2	0.917	0.917	0.914	0.911

*Notes: Coefficient on wind can be interpreted as \$/MWh. Congested = 1 if average price spread >1. Observations dropped if average price falls within the noted "donut". 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 - alternative standard errors

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) Total Dmg
Wind	-52.93***	-52.93***	-52.93***	-52.93***
	(0.567)	(1.476)	(1.656)	(1.932)
Wind*Congested	13.13***	13.13***	13.13***	13.13***
	(0.943)	(1.994)	(2.224)	(2.344)
Congested	-225,656	-225,656	-225,656	-225,656
	(165,470)	(264,388)	(331,872)	(399,744)
Clustering	Robust	Day	Week	Month
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	0.916	0.916	0.916	0.916

*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. 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 indicated level in parentheses. *** p<0.01, ** p<0.05, * p<0.1*

Table B.7: 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.8: 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.9: Average marginal effect of wind generation - Matched sample

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) 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.10: 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 14.

Total Load is the summed load across the zones givne in Figure 14.

Table B.11: 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.12: 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.13: 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.14: 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*

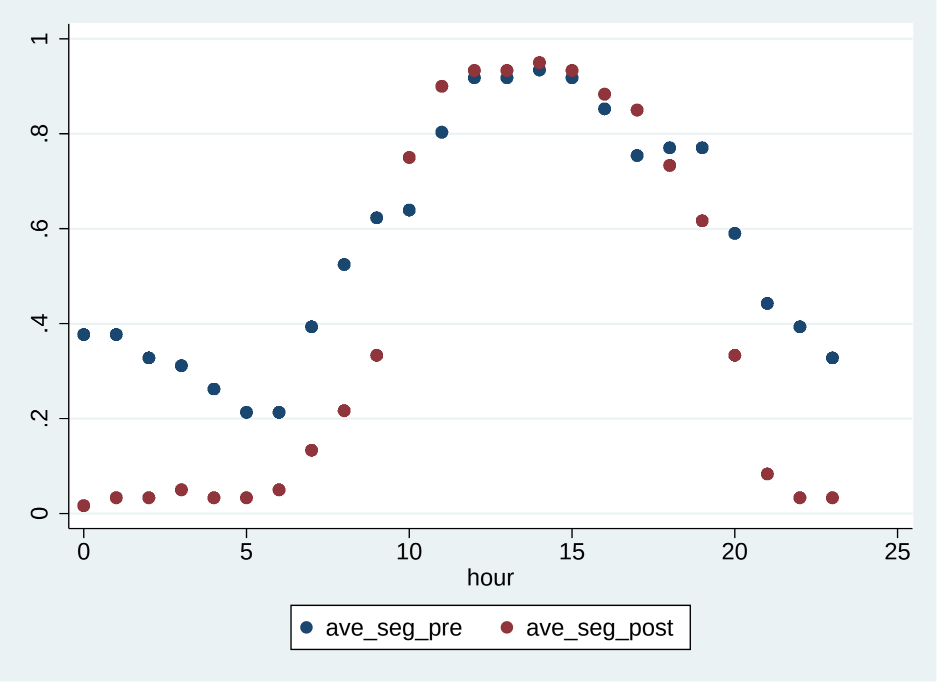

Figure B.1: Percent of hours that are congested in the two months pre- and post- major CREZ project completion on June 30, 2013.