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Emissions, Transmission, and the Environmental Value of Renewable Energy†

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We examine how transmission congestion alters the environmental benefits provided by renewable generation. Using hourly data from the Texas and midcontinent electricity markets, we find that relaxing transmission constraints between the wind-rich areas and the demand centers of the respective markets conservatively increases the nonmarket value of wind by 30 percent for Texas and 17 percent for midcontinent markets. Much of this increase in the nonmarket value arises from a redistribution in where air quality improvements occur—when transmission is not constrained, wind offsets much more pollution from fossil fuel units located near highly populated demand centers. (*JEL* L94, Q42, Q51, Q53)

Across the United States, large utilities spent roughly \$21 billion on electricity transmission infrastructure in 2016 alone, with billions more planned for future years (see Edison Electric Institute 2018). Much of this infrastructure has been and will continue to be built to deliver power from sparsely populated regions rich in renewable energy (wind and solar) to more populated regions where demand for electricity is much higher. Regional price differences driven by grid congestion give rise to obvious arbitrage opportunities. However, grid congestion (or the alleviation thereof through transmission expansion) may not only affect the private value of renewable energy, but also its social or environmental value. Specifically, congestion can impact the *level* and *location* of emissions avoided by renewable generation. In other words, transmission lines carry both the electrons as well as the improvements to local air quality that are produced by renewable energy.

In this paper, theoretical and empirical analyses are used to examine how grid congestion affects the environmental benefits of wind generation, explicitly accounting

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for spatially specific damages from local pollutants as well as damages from global pollutants. Our findings reveal that grid congestion can significantly reduce the environmental value of renewables. In particular, insufficient transmission capacity can prevent renewable generation produced in less-populated regions from reducing dirty fossil generation and thus local emissions in high-damage populated areas, illustrating that the *location* channel is critical in assessing the environmental value of renewable energy.

Our analysis employs several key features. First, we utilize county-specific damage estimates for local pollutants, allowing us to capture substantial heterogeneity in environmental damages associated with emissions from fossil plants. Second, our theoretical and empirical approaches allow us to examine how transmission and congestion affect the nonmarket value of wind generation, as well as how wind generation affects the nonmarket value of transmission. Third, we leverage rich hourly data to exploit significant variation in load conditions, wind generation, and grid congestion. Using market data to identify the existence of congestion raises some endogeneity concerns, so we employ recently developed machine learning techniques to generate parsimonious instrumental variables from a set of more than 1,700 plausibly exogenous instruments. Finally, we use our parameter estimates to assess the nonmarket value of a transmission expansion project completed in early 2014 in Texas.

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

Our empirical application, conducted separately for the Texas electricity market (ERCOT) and the market that encompasses much of the midcontinent portion of the United States (MISO), finds a consistent reduction of local and global emissions damages due to wind generation. Importantly, environmental damages offset by wind generation are lower, at statistically and economically significant levels, during periods of transmission congestion. For example, wind in ERCOT offsets $52 per MWh in uncongested periods, compared to only $40 per MWh in congested periods. In terms of mechanisms for this disparity, we find the marginal value of wind in terms of local pollutant reductions falls considerably during congested hours (the marginal value is lowered by 35 percent in ERCOT and 18 percent in MISO), but reductions in CO_2 damages are much less affected by congestion (marginal values are reduced by 8 and 7 percents, respectively, across ERCOT and MISO). Our estimates are robust to a battery of alternative assumptions and specifications, and our interpretation is well-supported by an array of analyses into the underlying mechanisms.

These findings have important consequences on several fronts. First, the serious health consequences of local air pollution have been well documented (Currie and Walker 2011; Schlenker and Walker 2016; Deschênes, Greenstone, and Shapiro 2017; Deryugina et al. 2018), and this paper highlights the role that transmission networks can play in moving air quality improvements from renewable-rich to renewable-poor areas. Second, while low and even negative market prices due to transmission congestion have received substantial attention, by robustly quantifying how transmission congestion reduces the environmental value of wind generation, our results show that the environmental consequences of grid congestion can also be quite serious.[1] This is particularly important for renewable generators as they have been heavily subsidized in large part on the grounds that they provide certain environmental benefits, and our results suggest that if this support for renewables is not also met with transmission infrastructure support, much of the perceived environmental value may be lost. Third, given the large sums of money being spent on transmission upgrades, our findings and analysis framework more generally are important in evaluating nonmarket values of these investments.[2] Indeed, we use our parameter estimates to calculate a back-of-the-envelope environmental value of a $7 billion transmission project undertaken in ERCOT—the Competitive Renewable Energy Zone (CREZ) upgrades that increased the transmission capacity between the wind-rich west portion of the market to the demand-rich east. Our results indicate that the reduced grid congestion brought about by the CREZ project increased the environmental value of ERCOT's wind generation by $366 million annually, with three-quarters of this value coming from decreased local-pollutant damages.

Our findings contribute to multiple strands of literature. Similar to the trade and the environment literature (Copeland and Taylor 1994; Antweiler, Copeland, and Taylor 2001; Davis and Kahn 2010; Cherniwchan 2017), we also assess how barriers to trade (in this case through transmission constraints) impact environmental outcomes, finding that transmission-related barriers to electricity trade are, on average, environmentally harmful. Our work is also related to the environmental economics literature on nonuniformly mixed pollutants and/or pollutants with location specific damages (e.g., Muller and Mendelsohn 2009, Holland and Yates 2015, Fowlie and Muller 2019). Despite the fact that support of renewable power has become one of the major environmental policies worldwide, this literature has not examined the indirect regulation of emissions with spatially heterogeneous damages through the support of renewable energy.

More directly related, there have been several studies assessing the environmental value of renewable energy (e.g., Callaway, Fowlie, and McCormick 2018; Fell

[1] The occurrence of negative energy prices due to grid congestion in renewable-rich regions like California and Texas has garnered a great deal of comment in the popular press. For example, see a recent *Bloomberg* article: "One Thing California, Texas Have in Common is Negative Power," April 5, 2016, https://www.bloomberg.com/news/articles/2016-04-05/one-thing-california-texas-have-in-common-is-negative-power.

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

and Kaffine 2018; Cullen 2013; Kaffine, McBee, and Lieskovsky 2013; Novan 2015). Here, we explicitly account for county-specific damages, and thus our estimates of the environmental value of wind generation are driven by both the type and location of avoided emissions. A related econometric application examines how the CREZ project affected private welfare measures (LaRiviere and Lu 2017), but does not account for how grid congestion alters the spatial pattern of location-specific emission damage reductions from wind generation. To our knowledge, this is the first econometric study that assesses the role that transmission constraints play in determining the nonmarket value of renewables.[3] As we show, this turns out to be quite important as congestion alters the levels and spatial pattern of pollution damages avoided by renewables.

I. Conceptual Framework

This section provides intuition as to how increases in transmission capacity can affect the nonmarket value of renewable generation. We extend the transmission models in Joskow and Tirole (2005) and LaRiviere and Lu (2017) to include renewables and a negative externality in the form of unpriced emissions. Using this stylized model, we highlight how the environmental damage avoided by additional renewable generation can vary across uncongested (transmission unconstrained) and congested (transmission constrained) periods.

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

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

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

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

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

When congested ($|Q| = K$), regional prices and marginal costs differ:

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

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

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

$$D(W) = \gamma_g\left[g_w(F_w(W)) + g_e(F_e(W))\right] + \delta_w s_w(F_w(W)) + \delta_e s_e(F_e(W)). \tag{3}$$

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

$$\frac{dD}{dW} = -\gamma_g\left(g_w'\frac{MC_e'}{MC_e' + MC_w'} + g_e'\frac{MC_w'}{MC_e' + MC_w'}\right) - \delta_w s_w'\frac{MC_e'}{MC_e' + MC_w'} - \delta_e s_e'\frac{MC_w'}{MC_e' + MC_w'}, \tag{4}$$

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

$$\frac{dD^c}{dW} = -\gamma_g g_w'(F_w^c) - \delta_w s_w'(F_w^c). \tag{5}$$

While inspection of equations (4) and (5) reveals the important distinction that wind in congested markets will only offset West fossil generation[5]—whereas wind in uncongested markets offsets fossil generation anywhere—direct comparison is complicated by the fact that the West emissions functions are evaluated at different levels of generation (F_w versus 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 $s_w'(F_w) = s_w'(F_w^c)$, and

[5] It is possible that wind generation may be curtailed due to transmission constraints, in which case wind would be marginal and fossil generation in the west would be zero or otherwise unresponsive to wind generation. In this case, $dD^c/dW = 0$.

simplify notation such that $\delta_e = \delta(1+\nu)$ and $\delta_w = \delta$, then the difference in damages offset by wind in uncongested versus congested markets is

$$(6) \qquad \frac{dD}{dW} - \frac{dD^c}{dW} = \underbrace{\left[\gamma_g\left(g_w' - g_e'\right) + \delta\left(s_w' - s_e'\right)\right]\frac{MC_w'}{MC_e' + MC_w'}}_{\text{emissions level effect}}$$

$$- \underbrace{\delta\nu s_e' \frac{MC_w'}{MC_e' + MC_w'}}_{\text{emissions location effect}}.$$

The *emissions level effect* reflects the change in damages as 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 that increased exports due to wind in the West will reduce local pollution in the East, which may have different marginal damages. The emissions level effect has an ambiguous impact on how congestion affects the environmental value of wind. For example, if the West were a heavy coal region (large g_w' and s_w') and the East was primarily gas (small g_e' and s_e'), the emissions level effect would lead to greater environmental value in congested periods. In contrast, if local marginal damages are higher in the East ($\nu > 0$), the emissions location effect unambiguously increases the environmental value of wind during uncongested periods relative to congested periods.[6]

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

II. Data and Methods

We analyze the environmental value of wind generation for MISO and ERCOT separately. These two market regions have the highest wind generation of all ISO/RTO regions in the United States and much of the wind generation is concentrated in the less-populated portions of their market footprints (see top panels of Figure 1), similar to the United States more generally and several other nations.[7]

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

[7] For example, China, which is currently investing more in renewable energy than any other nation, has a similar siting pattern. China has strong wind and solar generation potential in its more remote north and west regions, far

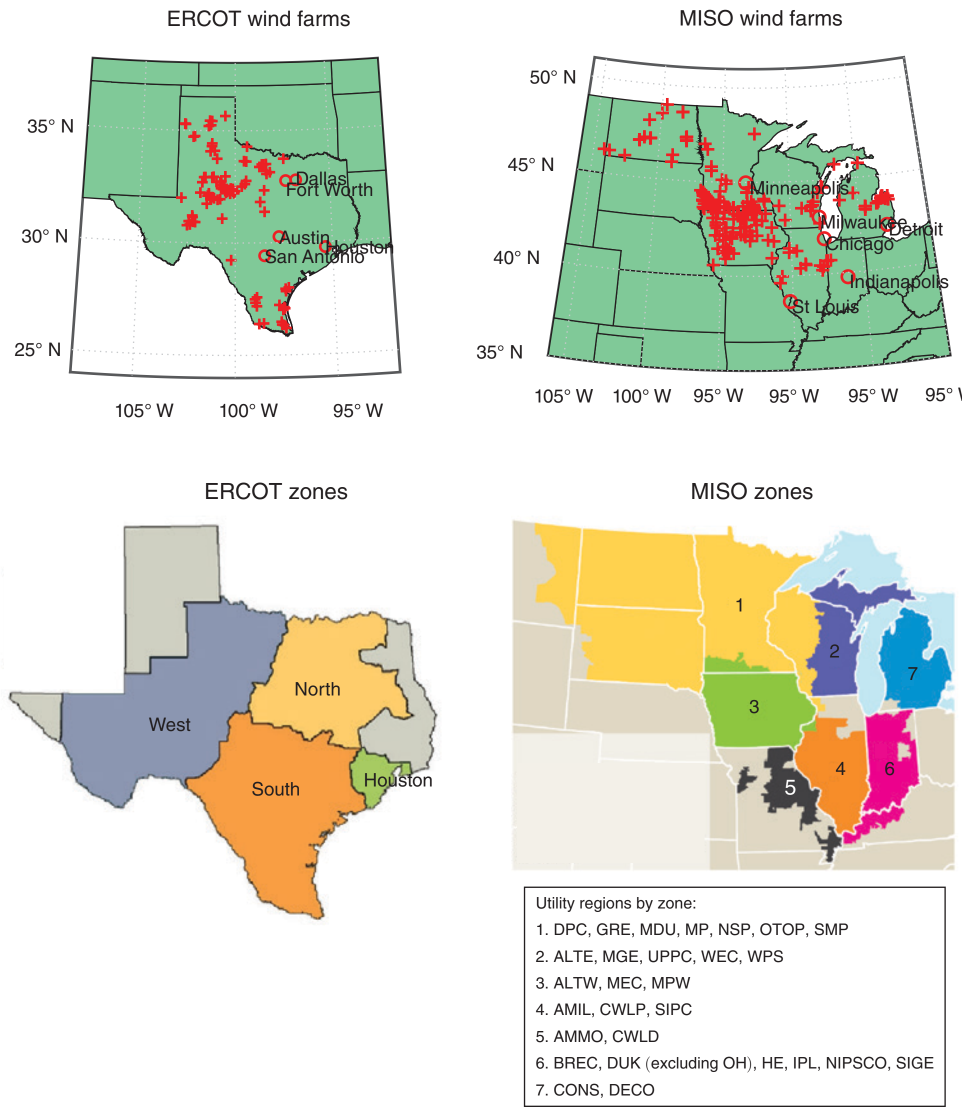

Figure 1. ERCOT and MISO Wind Farms (Source: EIA 860 Form from 2015) and Zones (Source: ERCOT and MISO, Respectively)

Based on plant-specific monthly generation in the EIA-923 data, over our sample the sparsely populated ERCOT West accounts for 70–85 percent of ERCOT's total wind generation and, similarly, wind generation from the less densely populated western states in MISO (Iowa, Minnesota, Montana, North Dakota, and South Dakota) account for 75–90 percent of MISO's wind generation.

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).

A. *Data*

We collect hourly data on generation, emissions, weather outcomes, and market conditions for each market region analyzed, ERCOT and MISO (Fell, Kaffine, and Novan 2020). We begin by creating measures of the hourly environmental damages from all electricity generators in the given market region. From the EPA's Air Markets Program Data (AMPD) database, we collect hourly generation and emission data from each generating unit.[8] In addition, using EIA 860 data, we identify the county of each generating unit. We then pair this emissions and location data with the estimated county-specific marginal damages associated with emissions of SO_2, NO_x, and PM2.5 as reported in Holland et al. (2016).[9] Thus, the market-region-wide environmental damages during any given hour h can be calculated as

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

where f_{ipch} represents the hourly emissions of pollutant p from plant i in county c during hour h and s_{pc} is the dollar damages per unit of pollutant p emitted in county c. While s_{pc} is constant across counties for CO_2, s_{pc} varies substantially across counties for SO_2, NO_x, and PM2.5.[10] Additional analyses disaggregate the market-wide damages into load zone-specific damages (see the bottom panels of Figure 1 for a map of the zones by market) as well as global damages (CO_2) and local damages (SO_2, NO_x, and PM2.5).

To highlight why the environmental value of wind generation may depend on the spatial pattern of the conventional generation that is offset, we first explore how the marginal damage from fossil fuel generators varies across the zones of each market region. Similar to the method employed by Callaway, Fowlie, and McCormick (2018) to obtain regional average marginal emission rates per MWh of fossil fuel generation, we regress the hourly damages in a given zone on the aggregate hourly fossil fuel generation in the corresponding zone, allowing the marginal effect of fossil generation to vary freely by the hour of day. For each zonal regression we use the full sample of data (2011 through 2015) and we include month-by-year and day-of-week fixed effects to flexibly control seasonal and weekly variation in

[8] While the AMPD database is the root source of the data (Environmental Protection Agency), we accessed these 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 (ABB). Additionally, we restrict the sample to generating units in the EIA-defined sectors of "non-cogen electric utility" or "non-cogen independent power producers" as these are the sectors likely to be participating in the ERCOT electricity market.

[9] Note, the AMPD data do not report hourly PM2.5 emissions and thus we impute these values. To do this, for each market region separately, 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 (Environmental Protection Agency). We regress these emissions on annual county-specific levels of generation from fossil-fuel-fired power plant technologies as reported through the AMPD database, along with year fixed effects. The technology-specific parameters then serve as our emission coefficients for generators of those respective types. For ERCOT we derive separate PM2.5 coefficients for plants burning coke, coal, and lignite, as well as coefficients for natural gas combined cycle (NGCC) and natural gas single cycle (NGSC) plants. For MISO we derive PM2.5 coefficients for plants burning coke, nonlignite coal, lignite coal, and diesel, as well as for NGCC and NGSC plants. Multiplying these coefficients by observed hourly generation gives the hourly PM2.5 emissions. Robustness checks in the appendices drop the imputed PM2.5 values.

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

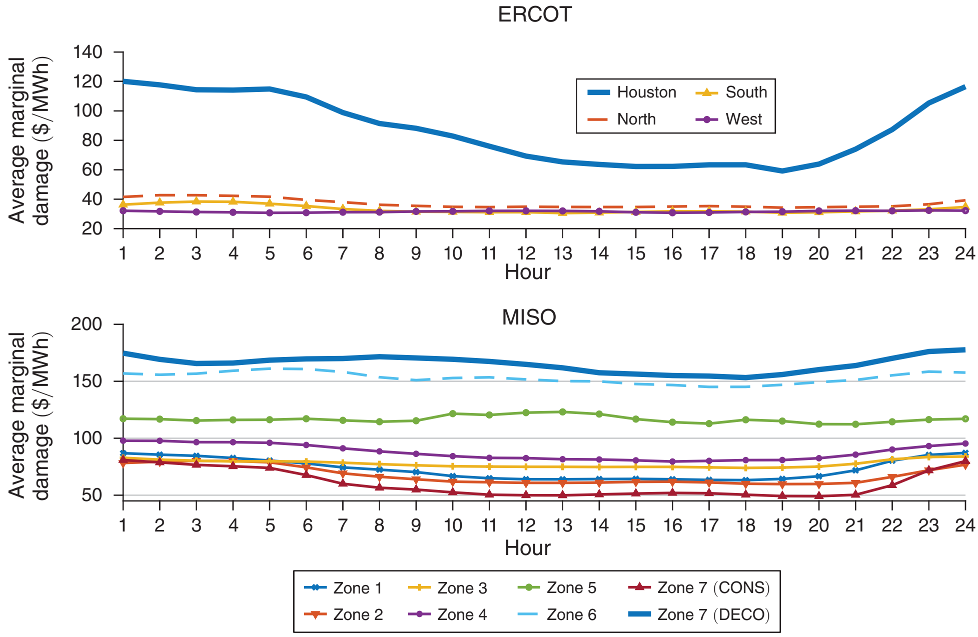

Figure 2. Damages from MWh of Fossil Generation across Market Region Zones

plant usages. Figure 2 displays the average marginal damage estimates per MWh of fossil generation for each zone and for each hour of day in the two market regions. For ERCOT, 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 on average less damaging, 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. Similarly, in MISO, the highly populated zones in the east part of the region, Zone 6 (most of Indiana) and Zone 7-DECO (southern Michigan including Detroit), have about double the average marginal damage per MWh of fossil fuel as the wind-rich zones (Zone 1 and Zone 3).

Ultimately, to show how the nonmarket value of wind varies with market conditions, we regress hourly environmental damages on hourly market-region wind generation, measures of market congestion, and importantly, a large set of controls. To control for shifts in electricity demand, we include hourly load (electricity consumed) at the market-region level and at the load-zone level.[11] Using data from FERC Form 714, we also control for load from neighboring regions, which includes the Southwest Power Pool (SPP) for ERCOT and SPP, PJM

[11] We obtained the zonal load data from ABB's Velocity Suite and it runs through 2015 for ERCOT and through 2014 for MISO. Because load and price data were available for each of the utility regions of zone 7 (Consumers Energy (CONS) and Detroit Edison (DECO) in MISO), 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. 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.

Table 1—Data Summary

	ERCOT		MISO	
	Mean	SD	Mean	SD
CO_2 damage ($)	797,561	226,315	1,681,668	315,859
SO_2 damage ($)	909,958	263,344	3,080,016	936,715
NO_X damage ($)	51,066	17,428	236,362	55,562
PM2.5 damage ($)	77,783	24,337	259,181	47,892
West RTM price ($/MWh)	35.62	86.94	–	–
South RTM price ($/MWh)	33.48	85.83	–	–
North RTM price ($/MWh)	32.00	80.02	–	–
Houston RTM price ($/MWh)	32.63	82.60	–	–
Zone 1 congest price ($/MWh)	–	–	−2.67	11.12
Zone 2 congest price ($/MWh)	–	–	−0.89	9.00
Zone 3 congest price ($/MWh)	–	–	−4.68	12.17
Zone 4 congest price ($/MWh)	–	–	−0.96	8.10
Zone 5 congest price ($/MWh)	–	–	−1.90	9.26
Zone 6 congest price ($/MWh)	–	–	0.87	8.18
Zone 7 (CONS) congest price ($/MWh)	–	–	2.03	14.00
Zone 7 (DECO) congest price ($/MWh)	–	–	1.38	11.32
Wind (MWh)	3,825	2,407	3,973	2,411
Congested	0.3808	0.4856	0.547	0.498
Total load (MWh)	38,288	9,240	58,717	9,712
Fuel price ratio	0.0155	0.0039	0.0169	0.009

Notes: Data are from 2011–2015 for 43,824 hourly observations in total. Damages represent average hourly damages associated with emissions from all plants in the respective markets.

Interconnection, Independent Electricity System Operator (Ontario) region, and the Tennessee Valley Authority balancing authority area for MISO. To control for changes in the merit order of generation units, we include natural gas-to-coal price ratios. For coal prices, we use the ABB Velocity Suite estimated plant-level coal cost, and form capacity weighted average prices by load zone. For the natural gas price, ABB assigns a gas hub 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 fuel price ratio is the ratio of these average prices. Table 1 provides summary statistics for the hourly damages from emissions, zonal prices, and other key explanatory variables used in our analysis. Note that average CO_2 damages per MWh in MISO are nearly 50 percent larger than in ERCOT, reflecting the higher coal-intensity of MISO generation.

We use several approaches, based on market-price dispersions, to classify whether the given market region is congested during a given hour. Given the homogeneity in the product (electricity), differences in prices across the market region at a given point in time are taken as a signal of system congestion. ERCOT, as with other ISO/RTO regions, clears both day-ahead and real-time electricity markets. While most of the electricity is contracted through the day-ahead market, we use real-time market prices in ERCOT to create our congestion metrics because the real-time spatial price differentiations reflect the congestion status at the time when the wind is actually generated. 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 each of the four zones (ERCOT ISO 2017).[12] Examination of the data suggests 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).[13]

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

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

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

For MISO, the congestion, line-loss cost, and zonal electricity prices are all published separately (Midcontinent ISO 2018), whereas all three of these components are embedded in the quoted zonal price in ERCOT. The MISO zonal congestion price gives the shadow value of the transmission constraint for the zone, where positive congestion prices imply the flow of power into the zone is restricted and a negative price implies restricted power flows out of a zone. We use these quoted congestion prices in MISO to define the congestion dummy such that the market is congested if one of the zonal congestion prices falls outside a specified price range. Formally, congestion C_{hdmy} in MISO is defined as

$$C_{hdmy} = \mathbf{1}\big(congest_{\min,hdmy} < -c \text{ OR } congest_{\max,hdmy} > c\big), \tag{9}$$

where $congest_{\min,hdmy}$ is the minimum of the eight congestion prices in a given hour, $congest_{\max,hdmy}$ is the maximum, 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

[12] ERCOT reports four zonal and four "hub" real-time prices. The hub price is a simple average of prices at resource nodes connected to the larger transmission points (345 kV) in the ERCOT system. Zonal prices are the MW-weighted prices of resource nodes within the zone and, unlike the hubs, all resource nodes are assigned to one of the zones. We use the zonal prices instead of the (similar highly correlated) hub prices as they capture all ERCOT prices and, through MW-weighting, give greater importance to large generation or load sources. We have also conducted the analysis using hub prices and they yield very similar results both qualitatively and quantitatively.

[13] 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.

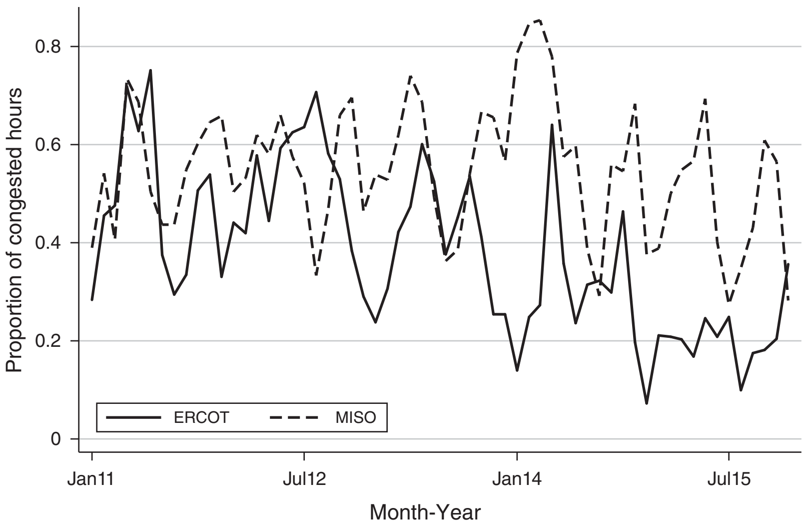

Figure 3. Proportion of Congested Hours by Month-Year

vary this to check for the sensitivity of our results (similar results are found under a zone averaging method as in ERCOT).

Using our base specification described above, we find the ERCOT market was congested 38 percent of the hours from 2011 through 2015, while MISO was congested 55 percent of the hours. Figure 3, which displays the proportion of congested hours for each month (i.e., share of hours $C_{hdmy} = 1$) of the sample for ERCOT and MISO, highlights that there is considerable variation in the frequency of congested hours. For ERCOT, Figure 3 displays a substantial drop-off in congested hours during 2014 and 2015, the years following the CREZ transmission expansions (based on ERCOT documentation, the bulk of CREZ is completed around mid-to-late 2013—see RS&H 2017 and online Appendix A).[14] We utilize the CREZ transmission expansions as an instrumental variable for congestion, which we describe in more detail below. For MISO, the variation in monthly congestion rates remains relatively constant between 0.4 and 0.7.

B. *Empirical Strategy*

The base regression specification takes the following form:

$$D_{hdmy} = \beta_1 W_{hdmy} + \beta_2 W_{hdmy} C_{hdmy} + \beta_3 C_{hdmy} + \sum_i \theta_i^j f_i(\mathbf{X}_{hdmy}) + \gamma_{hm} + \eta_{my} + \delta_d + \epsilon_{hdmy}, \tag{10}$$

[14] Variation in the average price spread over time (demeaned by hour-by-month fixed effects) is also shown in the online Appendix as Figure B.1.

where D_{hdmy} is ERCOT-wide or MISO-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 (MWh) in the given market region, and C_{hdmy}, which is an indicator for whether the market was congested; $\mathbf{X}_{hdmy}$ is a set of controls for load, fuel price ratio, and other variables described above, which typically enter as a quadratic. Fixed effects control for other sources of variation in our outcome variables that may be correlated with our explanatory variables of interest. Hour-by-month fixed effects γ_{hm} control for changes in wind patterns over the course of the day that may be correlated with changes in the shape or composition of the load profile. Month-by-year fixed effects η_{my} control for longer-run trends such as increasing wind capacity and changes in the generation mix (e.g., retirements). We employ day-of-week fixed effects δ_d to capture within-week variation in the load and generation profile. Finally, to account for serial correlation, standard errors are clustered at the month-year level.

Our key coefficients of interest are β_1, representing the marginal effect of wind generation on environmental damages when markets are uncongested, and β_2, representing the change in the marginal effect of wind generation when markets are congested. The expected sign on β_1 is negative—wind should displace fossil fuel, reducing environmental damages, and while the expected sign on β_2 is theoretically ambiguous per Section I, it may be positive if congestion prevents wind from offsetting high-damage fossil generation in more densely populated regions (e.g., Houston or Detroit).

One concern with estimating equation (10) is that the parameters may be biased if *Congested* is endogenous. Endogeneity may arise if, for example, unobserved plant outages due to plant maintenance affects both the probability of market congestion and the dispatch order (and thus emissions and associated damages). In particular, if this shift in the dispatch order due to plant maintenance systematically decreased emissions, this would negatively bias the β_2 coefficient, understating the diminished environmental value of wind in congested market conditions.[15]

For ERCOT, we apply instrumental variable approaches to address the potential endogeneity. For an instrument, we exploit the timing of CREZ transmission expansions (using variants of the percent volt-miles completed). As noted above, the CREZ expansion project increased transmission capacity from West to East Texas. This project was rolled out in phases over the course of our sample period, and this expansion should lower congestion rates but otherwise not affect damages associated with generation. To find other suitable instruments for congestion, we turn to the engineering literature regarding the capacity of electricity transmission lines. While transmission lines are given static capacity ratings, which often reflect a best-case scenario for the amount of power that can flow across the lines, ambient weather conditions such as wind speed and direction, air temperature, and solar radiation can affect the capacity

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

of a line in real time (Wang and Pinter 2014, Woerman 2018). As these ambient conditions affect transmission capacity levels, these will impact congestion rates in ways which, after controlling for electricity demand and other relevant observables, should be otherwise uncorrelated with observed emissions and satisfy the exclusion restriction.[16] We therefore collect hourly data from weather stations across Texas, then use these data to form county-level averages of the given weather variables.

We have a large set of possible instruments for ERCOT given all of the county-level weather variables, the interactions of these county-specific weather conditions with zonal load, wind generation, percent of CREZ completion, and total ERCOT load, as well as the squared terms of county-level weather, zonal load, and CREZ completion variables, alone and interacted. In all, this procedure gives us over 1,700 possible instruments. We use the IV-LASSO procedure as described in Belloni et al. (2012), wherein a LASSO estimator is used in the first stage to determine a more parsimonious set of instruments (56 in total) and standard IV estimation is then conducted given the selected set of instruments.[17]

III. Results

This section first presents the results from our base specification (equation (10)), which estimates the environmental value of wind in uncongested versus congested market conditions. We then decompose these values by showing the environmental value of wind in uncongested and congested states with respect to damages from local (SO_2, NO_x, $PM_{2.5}$) and global (CO_2) pollutants. This is followed by a series of robustness checks and a closer examination of the underlying mechanisms that drive the differences in the environmental value of wind.

A. *Environmental Value of Wind*

Estimation results of variants on equation (10) are given in Table 2, with panel A presenting the results for ERCOT and panel B presenting the MISO results. Total hourly environmental damages is the dependent variable.[18] The coefficient on *Wind*

[16] In practice, these ambient weather conditions may influence dispersion rates and exposure rates, which may affect real-time pollution damages "on the ground." However, from a technical perspective, because we are applying average damage rates by county s_{pc}, our total damage value can only be affected by weather conditions through changes in plant emissions f_{ipch}, which are conditioned on electricity demand and other relevant observables. As such, these weather variables satisfy the exclusion restriction with the potential caveat of local temperature effects on power plant capacities, though this effect does not have a clear, systematic bias on our estimates. We are assuming these weather variables have at most a second order impact on our damage rate estimates, given the vast differences in population between West Texas and the rest of the state.

[17] Note, using all 1,700 instruments creates a weak instrument problem in ERCOT. In the addition, the variants of the non-CREZ instruments are available for the MISO region. However, when applying a similar LASSO-IV approach based on these weather variables, zonal loads, and their interactions, resulting F-statistics indicate the procedure is likely suffering from a weak instrument problem. Specifically, using the two-step procedure for F-statistic calculations with multiple endogenous variables described in Angrist and Pischke (2009) and using the instruments selected from the IV-LASSO procedure, the F-statistic is only 1.7 and the Kleibergen-Paap rank Wald F-statistic is 4.6, indicating a clear weak instrument problem. Similarly, if we drop CREZ-related instruments from the IV procedure for ERCOT the F-statistic is only 2.8.

[18] Table 2 reports month-by-year cluster-robust standard errors. We also considered Newey-West standard errors with 168 lagged hours (one week of lagged values). The Newey-West standard errors are smaller, so we elected to report the more conservative clustered standard errors.

Table 2—Average Marginal Effect of Wind Generation on Environmental Damages

	Total damage (1)	Total damage (2)	Total damage (3)	Total damage (4)	Total damage (5)	Total damage (6)
Panel A. ERCOT						
Wind	−51.65	−50.30	−52.77	−51.84	−52.35	−54.65
	(3.314)	(1.647)	(1.905)	(1.823)	(1.887)	(3.183)
Wind × Congested	8.832	12.10	11.63	9.791	12.36	19.99
	(2.968)	(2.117)	(1.980)	(1.795)	(2.263)	(8.599)
Congested	4,220	−62,095	−58,751	−50,393	−239,890	−121,458
	(15,731)	(9,603)	(9,228)	(8,500)	(387,872)	(62,811)
Load		69.27	68.62			
		(4.867)	(5.506)			
Load^2		−0.0004	−0.0003			
		(5.46e−05)	(6.43e−05)			
Fuelratio		5.015e+07	5.172e+07	5.209e+07		
		(1.788e+07)	(1.701e+07)	(1.700e+07)		
Fuelratio^2		−8.589e+08	−8.459e+08	−8.369e+08		
		(2.840e+08)	(2.675e+08)	(2.673e+08)		
Additional controls	N	N	Y	Y	Y	Y
Zonal load	N	N	N	Y	Y	Y
Fully interacted	N	N	N	N	Y	N
IV	N	N	N	N	N	Y
Observations	43,824	43,824	43,824	43,824	43,824	43,824
R^2	0.817	0.912	0.914	0.916	0.919	0.915
Panel B. MISO						
Wind	−55.29	−83.29	−80.11	−86.57	−88.89	
	(11.21)	(4.675)	(4.713)	(5.330)	(4.731)	
Wind × Congested	−29.48	9.011	6.503	9.054	13.06	
	(10.29)	(3.922)	(3.823)	(4.221)	(3.776)	
Congested	177,457	−52,403	−50,198	−58,490	−1.131e+06	
	(38,975)	(17,173)	(15,320)	(15,172)	(571,209)	
Load		156.4	82.33			
		(12.31)	(16.10)			
Load^2		−0.0005	−0.0001			
		(0.000105)	(0.000114)			
Fuelratio		3.345e+07	2.717e+07	2.909e+07		
		(1.040e+07)	(9.217e+06)	(1.180e+07)		
Fuelratio^2		−1.916e+08	−1.615e+08	−1.707e+08		
		(5.871e+07)	(5.207e+07)	(6.835e+07)		
Additional controls	N	N	Y	Y	Y	
Zonal load	N	N	N	Y	Y	
Fully interacted	N	N	N	N	Y	
Observations	43,824	43,824	43,744	35,000	35,000	
R^2	0.848	0.954	0.959	0.950	0.952	

Notes: Coefficient on wind can be interpreted as \$/MWh. *Congested* = 1 if average price spread > 1 and if the congestion price is less than −4 or greater than 4 in MISO. "Load" is market-region-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 control variables in all specifications include linear and quadratic: average gas price/average coal price, average state temperatures, load from surrounding market regions, SPP Wind, and linear and quadratic zonal load controls. Fully interacted model interacts all controls (including fixed effects) with *Congested* variable. Cluster robust standard errors at month-by-year in parentheses.

corresponds to β_1 and the coefficient on *Wind* interacted with *Congested* corresponds to β_2, and these can be readily interpreted as the average dollar change in environmental damages due to a one MWh increase in wind generation in uncongested (β_1) versus congested $(\beta_1 + \beta_2)$ hours.

Column 1 of Table 2 is the most parsimonious specification and includes controls of only month-year, hour-month, and day of week fixed effects in addition to the *Wind*, *Wind* $\times$ *Congested*, and *Congested* variables. Column 2 adds linear and quadratic controls for total market-region-wide load and fuel price ratios. Column 3 adds linear and quadratic controls for average state-level temperatures as well as wind generation from the Southwest Power Pool (SPP) and load in the neighboring regions as described in Section IIA.[19] Column 4 replaces total market-region-wide load with linear and quadratic controls for the zonal loads in each market region, while column 5 fully interacts all controls and fixed effects from column 4 with *Congested*.

Results across Table 2 consistently find that the environmental value of wind is greater in uncongested hours compared to congested hours, with the exception being the column 1 results for MISO.[20] For each market region, coefficients on *Wind* and *Wind* $\times$ *Congested* are numerically similar across columns 2–5, which have an increasing number of relevant controls, including controls for region-wide or zonal loads and coal-to-gas fuel price ratios.[21] Comparing values across regions, we find the environmental value of wind generation is considerably higher in MISO, which is as expected given the prevalence of emissions-intensive coal generation in MISO and the greater number of large population centers (i.e., high environmental damage locations) in MISO.

Taking column 5 as the preferred specification, during uncongested market conditions an additional MWh of ERCOT wind generation offsets around \$52 in environmental damages. In contrast, during congested conditions, the environmental value of an additional MWh of wind falls to roughly \$40/MWh—a drop of approximately \$12/MWh. In other words, wind is 30 percent more environmentally valuable when the ERCOT market region is uncongested. Similarly, the environmental value of wind in MISO is about \$76/MWh in congested periods compared to \$89/MWh in uncongested hours, or an increase of about 17 percent when moving from congested to uncongested hours.

[19] Temperature may affect damages independent of load through effects on thermal efficiency of plants. Average temperature is based on hourly readings at ASOS stations across Texas for ERCOT and across Indiana, Minnesota, Michigan, Missouri, Montana, North Dakota, and Iowa for MISO, accessed from NOAA's Integrated Surface Database https://www.ncdc.noaa.gov/isd.

[20] Note for MISO, simply adding total MISO load as a control provides parameter estimates that are numerically similar to those shown in columns 2–5 of Table 2. This is expected given the large and significant effect load has on total damages in ERCOT and that load and MISO wind are negatively correlated, with that negative correlation increasing in magnitude in congested periods.

[21] The signs on the coefficients 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)).

For ERCOT, results from the IV-LASSO procedure described above are shown in column 6.[22] The IV-LASSO results also indicate a decrease in the environmental value of wind generation during periods of grid congestion, with an even larger estimated loss in environmental value of wind generation in congested periods. Based on the IV-LASSO results, the environmental value of wind falls by about 37 percent in congested periods versus 19–24 percent based on the OLS estimates.

Why are the IV estimates of the parameter on the wind and congestion interaction term larger? There are several possibilities. First, to the extent *Congested* is endogenous, the IV estimates may be correcting this in a way that leads to larger *Wind* × *Congested* parameter estimates. Another issue may be that if *Congested* is not truly binary as modeled here, then Angrist and Imbens (1995) show that IV estimates may be biased upward. To further explore this issue, we consider cuts of the data whereby we drop observations where the average price spread is relatively low in an effort to identify more binary congested and uncongested states. We consider four such settings where we drop all observations when the average price spread is between (i) 0.5 and 1.5; (ii) 0.1 and 5; (iii) 0.01 and 10; and (iv) 0.001 and 15. Parameter estimates on the *Wind* × *Congested* interaction term from the IV strategies are consistently, and considerably, higher than the OLS parameter estimates (see online Appendix Table B.1), providing evidence a potentially non-binary *Congested* variable is not driving the larger IV parameter estimates. It is also possible that we are picking up a local average treatment effect (LATE). Specifically, if the instruments explain the variation in congestion in periods prone to a larger loss in the environmental value of wind, we may be picking up that the LATE differs from the overall average effect. Regardless, the OLS estimates appear to conservatively estimate the impact of congestion on the environmental value of wind. That said, it should be noted the IV-LASSO results for the parameters on *Wind* and *Wind* × *Congested* are not statistically different from the OLS results. We therefore proceed with a variety of robustness checks and investigations of mechanisms using OLS estimation to demonstrate that, even with more conservative estimation approaches, the impacts of congestion on the environmental value of wind are statistically and economically significant.

B. *Local versus Global Pollutants*

To determine if the loss in environmental value during congested hours is driven by local or global pollutants, we estimate our fully-interacted models and, for ERCOT, IV-LASSO models with damages from local pollutants (SO_2, NO_x and PM2.5) or global pollutants (CO_2) as the dependent variable. The estimates are displayed in columns 1–4 of Table 3. Results for both MISO and ERCOT reveal the difference in environmental value in congested versus uncongested periods is primarily driven by changes in local pollutant damages. For ERCOT, of the \$12/MWh difference in total damages, \$10/MWh can be attributed to local damages versus

[22] We implement the IV-LASSO procedure in STATA using the "ivlasso" command. This command calls the "rlasso" command that employs of the penalization method for the "rigorous" lasso as described in Belloni et al. (2012). Fifty-six variables are selected as instruments.

Table 3—Average Marginal Effect of Wind Generation—Local versus Global

	Local damage (1)	Local damage (IV-LASSO) (2)	CO_2 damage (3)	CO_2 damage (IV-LASSO) (4)	Local damage (average) (5)	Local damage (median) (6)
Panel A. ERCOT						
Wind	−30.50	−31.81	−21.86	−23.17	−24.68	−17.43
	(1.682)	(2.819)	(0.427)	(0.771)	(1.352)	(0.931)
Wind × Congested	10.59	15.49	1.762	4.50	7.879	5.390
	(2.015)	(7.582)	(0.463)	(2.082)	(1.753)	(1.208)
Congested	−158,628	−94,728	−81,262	−26,731	−333,238	−207,343
	(345,657)	(54,554)	(60,549)	(14,840)	(233,990)	(160,697)
Fully interacted	Y	N	Y	N	Y	Y
Observations	43,824	43,823	43,824	43,823	43,824	43,824
R^2	0.822	0.814	0.985	0.984	0.875	0.874
Panel B. MISO						
Wind	−59.25		−29.65		−56.35	−51.24
	(4.472)		(0.821)		(3.868)	(3.532)
Wind × Congested	10.79		2.268		7.009	6.415
	(3.484)		(0.755)		(3.004)	(2.745)
Constant	−2.258e+06		−645,476		−1.909e+06	−1.742e+06
	(623,871)		(135,481)		(529,608)	(483,120)
Fully interacted	Y		Y		Y	Y
Observations	35,000		35,000		35,000	35,000
R^2	0.932		0.978		0.943	0.943

Notes: Coefficient on wind can be interpreted as \$/MWh. *Congested* $=$ 1 if average price spread $>$ 1 for ERCOT and if the congestion price is less than −4 or greater than 4 in MISO. Columns 5 and 6 replace county-specific local pollutant damages with market-region-wide average and median values, respectively. Columns 2 and 4 instrument for *Congested* and *Wind* × *Congested* in ERCOT using the IV-LASSO technique. Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Control variables in all specifications include linear and quadratic: average gas price/average coal price, temperature, load from surrounding market regions, SPP Wind, and linear and quadratic zonal load controls. Fully interacted model interacts all controls (including fixed effects) with *Congested* variable. Cluster robust standard errors at month-by-year in parentheses.

less than \$2/MWh from CO_2. Similarly in MISO, of the \$13/MWh environmental value of wind generation lost during congested periods, \$11/MWh comes from local damages and only about \$2/MWH is from CO_2.

Recall, under certain assumptions, there are two channels through which congestion can affect the environmental value of wind—the emissions level effect and the emissions location effect. For example, the small benefit of increased offsets of CO_2 emissions during uncongested hours is driven by the emissions level effect, indicating that the composition of the generators that respond to wind is different during uncongested periods.

To more closely explore the emissions level and location effects, we next consider cases where we remove the spatial variation in damages from local pollutants. Doing so isolates the emissions level effect, as a unit of emissions has the same environmental damage regardless of where it is emitted. Columns 5 and 6 of Table 3 replace the spatially explicit damages from local pollutants with the mean or median damages, respectively, across all counties with a fossil generator in the given market region. For both ERCOT and MISO, removing the spatial variation leads to an environmental value of wind in uncongested hours that is lower than in Table 2, and the

TABLE 4—AVERAGE MARGINAL EFFECT OF WIND GENERATION—ERCOT LEVELS VERSUS LOCATION

	CO_2 damage (1)	CO_2 damage (2)	Local damage (3)	Local damage (4)	Local damage (5)	Local damage (6)
Wind	−18.33	−16.61	−13.70	−9.866	−10.12	−7.125
	(0.786)	(0.896)	(2.465)	(3.088)	(1.569)	(2.390)
Wind × Congested	−0.492	−2.133	3.484	2.158	2.119	0.587
	(0.879)	(1.064)	(3.076)	(3.527)	(2.041)	(1.953)
Congested	−136,836	−178,266	−1.014e+06	−922,909	−327,291	−245,387
	(94,369)	(104,797)	(380,585)	(503,633)	(215,987)	(315,319)
Observations	9,958	5,182	9,958	5,182	9,958	5,182
R^2	0.988	0.988	0.790	0.808	0.864	0.868

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

interaction between *Wind* and *Congested* with spatially uniform damages is about 50–70 percent of the value it is with spatially explicit damages. For ERCOT, this suggests that, of the \$12 increase in environmental value during uncongested hours found in column 5 of 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).[23] In MISO, of the \$13 increase in environmental value of wind during uncongested periods, approximately 30 percent of that can be attributed to the emissions location effect and 70 percent to the emissions level effect.

We next consider a set of cases where we expect the emissions level effect to be near-zero. We use data from ERCOT only for this analysis as its generation profile with a single coal plant in its West zone makes it easier to isolate the emissions level effect. Specifically, we examine subsets of the data where the lone coal plant in the West zone is operating near full capacity (capacity factors in excess of 0.80), likely capturing hours in which natural gas units are on the margin in the West. As expected, results in column 1 of Table 4 show that, in uncongested periods, wind offsets less CO_2 damage than in Table 3, and the interaction effect is negative and insignificant. Column 2 restricts the sample further to observations where prices in ERCOT West and North are greater than \$35 per MWh, such that gas is almost certainly marginal in both regions. The interaction effect is now even more negative and marginally significant.[24] Looking at local damages in these same scenarios

[23] This is consistent with estimates in online Appendix Table B.2, 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).

[24] This could be noise, or it may reflect differences in CO_2 emission rates of CC versus CT. For example, congestion may lead marginal wind generation to offset inefficient, dirtier CT plants in ERCOT West, whereas

finds small positive and insignificant interaction effects (columns 3 and 4), consistent with gas as the marginal unit, but where the emissions location effect may still be positive due to greater population outside ERCOT West. Finally, in columns 5 and 6, we examine local damages where we zero out the emissions location effect by replacing county-specific damages with the median damages, leading to interaction effects that are very close to zero. In sum, Table 4 (i) illustrates a case where the emissions level effect is zero or even possibly negative, and (ii) shows that if we shut off differences in emission rates (approximately) to zero out the emissions level effect and shut off differences in county-specific damages to zero out the emissions location effect, then congestion does not affect the marginal environmental value of wind.

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 and MISO markets are congested, wind power located primarily in western parts of these market regions is unable to offset fossil generators in the more populated eastern parts of the market regions. In contrast, when uncongested, wind power in the western areas is more valuable as it can offset dirtier fossil generation in populated eastern areas. This is particularly stark in ERCOT where the region's major population center, Houston, has marginal damages from fossil generation that are very large (Figure 2).

C. *Robustness Checks*

Next, we consider a series of robustness exercises; in this section and in subsequent sections, we discuss the results in the context of ERCOT while including qualitatively similar findings for MISO in the online Appendix. The base specification for ERCOT classifies congested market conditions as hours where the average price spread across zones was greater than \$1. While this cutoff is somewhat arbitrary, we can examine whether varying this cutoff affects the estimated environmental value of wind. There are likely classification error tradeoffs in either direction. Lowering the cutoff means some hours where the market was basically uncongested will be classified as congested, while raising the cutoff means some hours where at least some portion of the market was congested will be classified as uncongested. Columns 1–5 of online Appendix Table B.4 set the cutoffs for congested hours at \$0, \$0.1, \$0.5, \$3, and \$5, respectively. Regardless of the cutoff, results are similar to those above in both uncongested and congested hours.[25]

We also examine alternative ways of defining the *Congested* variable in equation (10). First, online Appendix Table B.9 defines three pairwise *Congested* variables, corresponding to whether the price spread between ERCOT West and each of

that same wind generation would offset more efficient CC plants in ERCOT North in the absence of congestion constraints.

[25] To further confirm *Congested* should be treated as a binary variable, in online Appendix Table B.7 we define *Congested* as a continuous variable based on average price spreads, and in online Appendix Table B.8, we define *Congested* as a series of treatments based on average price spread bins (e.g., \$5–\$10). If the binary measure is appropriate, we would expect the continuous measure to yield a positive and noisy estimate of *Wind* × *Congestion* as in online Appendix Table B.7, and we would expect the binned estimates of *Wind* × *Congestion* to be fairly invariant across the price bins, as we see in online Appendix Table B.8.

Table 5—Average Marginal Effect of Wind Generation—ERCOT Zonal Impacts

	Total damage Houston (1)	Total damage North (2)	Total damage South (3)	Total damage West (4)
Wind	−23.30	−18.57	−9.435	−1.587
	(1.626)	(0.854)	(0.498)	(0.166)
Wind × Congested	8.936	3.107	1.928	−0.905
	(2.171)	(1.114)	(0.748)	(0.187)
Congested	73,347	−154,963	−256,459	91,214
	(318,047)	(131,349)	(100,623)	(24,337)
Observations	43,824	43,824	43,824	43,824
R^2	0.730	0.898	0.892	0.729

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

the other three zones exceeds \$1. That is, $C^{j}_{hdmy} = \mathbf{1}(|P_{West,hdmy} - P_{j,hdmy}| > c)$, where j is North, South, and Houston. Second, online Appendix Table B.10 defines a single *Congested* variable based solely on the price spread between the noted zones in each column, $C^{ij}_{hdmy} = \mathbf{1}(|P_{i,hdmy} - P_{j,hdmy}| > c)$, where i, j index each of the zones. Online Appendix Table B.11 defines congestion based on price spreads between West and the other three zones. Results are consistent with the base model presented in Table 2, which is not surprising due to the high degree of correlation between the various measures of congestion.

Finally, while our base specification assumes solely contemporaneous effects between wind and environmental damages, wind generation at hour t may hypothetically affect power plant operations at some point $t + n$ in the future, e.g., due to ramping or effects on emission control technologies (Kaffine, McBee, and Lieskovsky 2013). To capture any intraday spillovers between hours, online Appendix Table B.12 aggregates to the daily level (Novan 2015), yielding estimates of environmental damages avoided that are very similar to the hourly estimates.

D. *Mechanisms*

Recall a reasonable explanation for the increased value of wind in uncongested conditions is that transmission allows wind generated in the west to offset generation in more populated areas to the east. Table 5 presents estimates of equation (10) using total environmental damages by zone as the dependent variable, and the results are consistent with the above story. Focusing on the coefficient on *Wind* × *Congested*, it is positive and economically and statistically significant for ERCOT Houston, implying smaller environmental benefits in ERCOT Houston when markets are congested. In contrast, for ERCOT West, the interaction coefficient is negative and significant, implying larger environmental benefits in ERCOT West from wind when markets

Table 6—A Tale of Two Coal Plants: Oklaunion and W.A. Parish

	Oklaunion generation (1)	W.A. Parish generation (2)	Oklaunion damages (3)	W.A. Parish damages (4)
Panel A. All observations				
Wind	−0.0109	−0.0667	−0.222	−19.10
	(0.00206)	(0.00450)	(0.0421)	(1.289)
Wind × Congested	−0.00921	0.0314	−0.188	8.999
	(0.00242)	(0.00665)	(0.0493)	(1.905)
Congested	914.4	428.1	18,640	122,536
	(300.2)	(963.4)	(6,120)	(275,763)
Observations	43,824	43,824	43,824	43,824
R^2	0.631	0.731	0.631	0.731
Panel B. Hours with positive generation				
Wind	−0.0152	−0.0693	−0.310	−19.83
	(0.00169)	(0.00465)	(0.0345)	(1.331)
Wind × Congested	−0.0120	0.0341	−0.246	9.748
	(0.00255)	(0.00643)	(0.0520)	(1.841)
Congested	569.3	762.3	11,606	218,214
	(257.2)	(1,328)	(5,243)	(380,015)
Observations	35,488	26,762	35,488	26,762
R^2	0.631	0.720	0.631	0.720

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

are congested. Due to population differences, there is ultimately a net reduction in environmental damages avoided during congested periods.[26]

We can further show the consistency of the general story by drilling down to specific coal plants—the W.A. Parish coal plant (four units with a total capacity of 2.7 GW), which is located in the Houston suburbs (metro population 6.7 million) and is the only coal plant in the Houston zone and the Oklaunion coal plant (a single unit with 720 MW capacity) that is in Wilbarger County ("metro" population 13,000) and is the sole coal plant in the West zone. Table 6 estimates generation and environmental damage responses to wind in uncongested and congested periods at these two plants, yielding estimates consistent with the story above.[27] Oklaunion is twice as responsive to wind in congested hours, while W.A. Parish is half as

[26] 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.

[27] This plant-specific analysis is illustrative of the more general point that congestion creates important locational consequences for which plants respond to wind generation. However, the data for this analysis are based on a stylized sample that potentially introduces selection bias.

responsive when transmission constraints limit the ability of ERCOT West wind to influence fossil generation in ERCOT Houston.

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

To explore this issue in more depth, we separate our congested variable into two mutually exclusive dummies indicating whether the market is congested and ERCOT West prices are lower than average (*NegCongested*) or if the market is congested and ERCOT West prices are higher than average (*PosCongested*). The market is congested in 38 percent of hours, with about half the hours negatively congested and half the hours positively congested across the sample.[28] Table 7 reports estimates of equation (10) with *Wind* interacted with both *NegCongested* and *PosCongested*. Consistent with our hypothesis that, in congested hours, wind will tend to offset West generation regardless of the sign of the price spread, the environmental value of wind is similar across both negatively and positively congested hours despite reflecting very different states of the market.

E. *Heterogeneous Effects*

To further explore the impact of congestion on the environmental value of wind, we examine the heterogeneity in damages avoided across three temporal dimensions: yearly, seasonally, and hourly. During the time period of our sample, there were substantial changes in the electricity sector due to transmission expansions such as CREZ, growth in renewable generation, and variation in fuel prices. As such, if our results were driven by a single year, this may raise concerns that some omitted variable was biasing our findings. In online Appendix Table B.14, 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/MWh across years, while in congested hours, the environmental value is reduced by around \$13/MWh.[29]

Next, to see if there is seasonal heterogeneity due to differing loads or maintenance schedules, in online Appendix Table B.16, we split the sample into off-peak

[28] While on average the relative frequency of negative and positive congestion are roughly equal, this does change over time. In 2011, negative congestion occurs twice as often as positive congestion, while in 2012, positive congestion occurs about 50 percent more often than negative congestion. From 2013 onward, the overall frequency of congestion falls, with roughly equal positive and negative congestion.

[29] Note the uncongested environmental value of wind is somewhat higher in 2011 due to higher emissions intensity of fossil generation.

Table 7—Average Marginal Effect of Wind Generation—ERCOT Positive versus Negative Price Spreads

	Total damage (1)	Local damage (2)	CO_2 damage (3)
Wind	−52.35	−30.50	−21.86
	(1.895)	(1.689)	(0.429)
Wind × NegCongested	19.57	17.52	2.056
	(3.938)	(3.471)	(0.816)
Wind × PosCongested	12.44	10.79	1.650
	(2.853)	(2.584)	(0.558)
NegCongested	−573,940	−461,704	−112,235
	(435,154)	(385,586)	(65,571)
PosCongested	552,787	611,176	−58,389
	(381,490)	(331,801)	(79,153)
Observations	43,824	43,824	43,824
R^2	0.921	0.827	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 percent of observations). *PosCongested* $=$ 1 if average price spread $>$ 1 and ERCOT West price is above ERCOT average (18.6 percent of observations). Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Control variables in all specifications include linear and quadratic: average gas price/average coal price, temperature, SPP wind, SPP load, and linear and quadratic zonal load controls for ERCOT West, North, South, and Houston loads. All specifications are fully interacted models, which interacts all controls (including fixed effects) with *NegCongested* and *PosCongested* variables. Cluster robust standard errors at month-by-year in parentheses.

"shoulder months" (March, April, October, November) and nonshoulder months. The environmental value of wind in uncongested conditions is identical across shoulder and nonshoulder months, and the coefficient on *Wind* × *Congested* is larger in nonshoulder months, though not statistically distinguishable ($p = 0.143$).

Finally, because different fossil units are marginal during different hours of the day, the environmental value of wind will also likely vary by hour of day. Figure 4 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, McBee, and Lieskovsky 2013; 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, for example by \$13 per MWh at midnight. This is roughly equivalent to the difference between the environmental value of wind in mid-day versus overnight hours in uncongested conditions. While the prior literature has noted the importance of the fact that the environmental benefits from wind depend on whether coal or gas is marginal at different times of day, this figure shows the effect of transmission constraints and market congestion can be of an approximately equivalent magnitude.

F. *Total Effects of the Congested Variable*

Beyond directly affecting emissions damages, wind can indirectly affect damages via the probability that markets are congested. Consider a model of emission

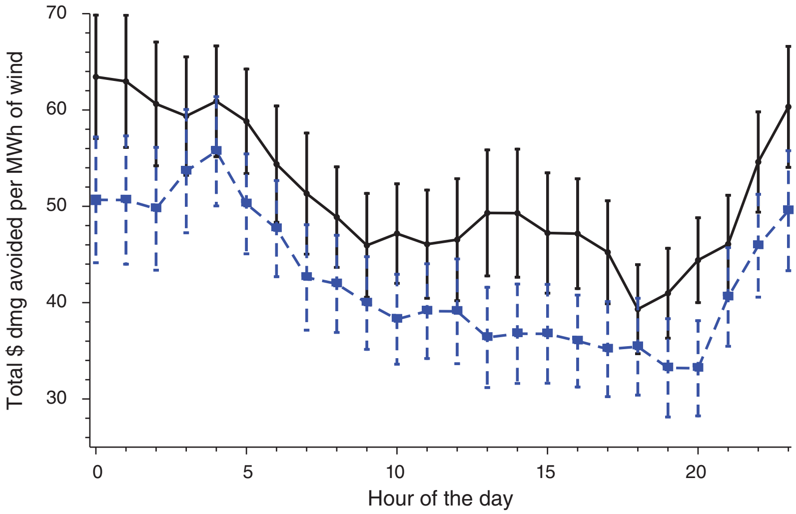

Figure 4. Environmental Value of Wind by Hour in Uncongested (Solid) and Congested Periods (Dashed) in ERCOT

damages conceptually similar to equation (10) that explicitly recognizes that congestion depends on wind generation:

$$D(W) = \beta_1 W + \beta_2 W \times C(W) + \beta_3 C(W). \tag{11}$$

Then the total derivative of damages with respect to wind is

$$\frac{dD}{dW} = \big(\beta_1 + \beta_2 C(W)\big) + (\beta_2 W + \beta_3)\frac{dC}{dW}. \tag{12}$$

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

To gain a sense of the empirical magnitude of this indirect effect, online Appendix Table B.18 estimates a series of specifications analogous to Table 2 (columns 1–4), but where the ERCOT indicator for *Congested* is the dependent variable of a linear probability model and ERCOT *Wind* is our variable of interest. Across specifications, this coefficient is remarkably consistent. Taking mean wind levels from Table 1, estimates of β_2 and β_3 from Table 2, and the estimate of dC/dW from column 4 of online Appendix Table B.18, the second term is equal to: $(\beta_2 W + \beta_3)(dC/dW) = (9.791 \times 3{,}825 - 50{,}393) \times 0.0000465 = -\$0.60/\text{MWh}\,(\pm\$0.47/\text{MWh})$. That is, at the mean wind generation level, the indirect effect of wind on damages through changes in the probability the ERCOT market is congested is less than a dollar per MWh, or an order of magnitude or two smaller than the main effects. The magnitude of the indirect effect for MISO is similar, though slightly larger and noisier: $-\$1.88/\text{MWh}\,(\pm\$1.43/\text{MWh})$.

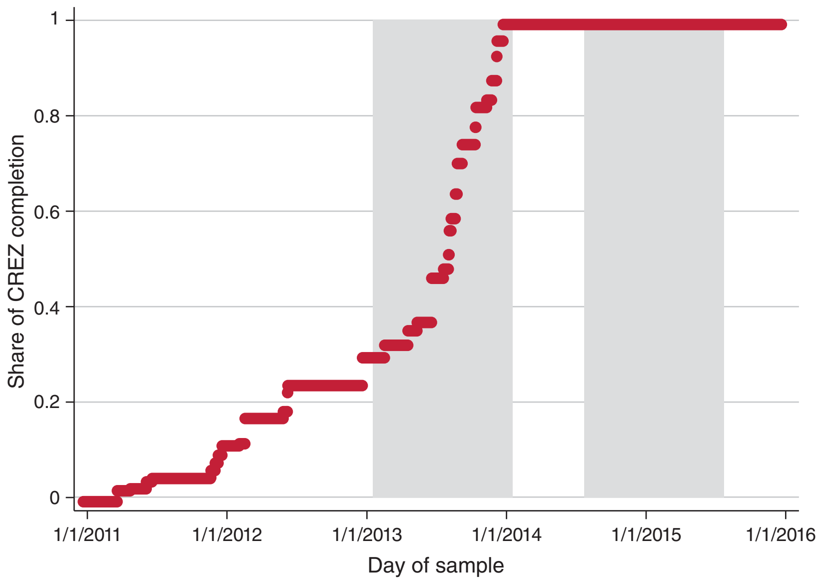

Figure 5. Share of CREZ Completion with Shaded Pre-/Post-CREZ Jump Samples (Source: ERCOT)

IV. Implications and Additional Considerations

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

To shed light on how much the environmental value of wind generation increased as a result of the CREZ transmission expansions, we first need to quantify how much the CREZ upgrades reduced the frequency of congestion. Causally measuring this effect is challenging given that the new CREZ lines were steadily energized over the sample period (Figure 5). Nonetheless, to produce a back-of-the-envelope estimate, we first compare the unconditional congestion frequency in 2011–2012 (pre-CREZ) versus 2014–2015 (post-CREZ). Markets were congested roughly half the time (49.7 percent) in 2011–2012, and that fell by half (25.3 percent) in 2014–2015, or a decline in congestion of 24.3 percentage points. Using the coefficient estimates in Table 2, 2015 average hourly wind generation of 4,649.3 MWh, and the unconditional change in the probability of congestion suggests a roughly \$122 (OLS) to \$198 (IV-LASSO) million annual increase in the environmental value of wind due to increased market integration.

However, this simple approach fails to account for changing market conditions. For example, average hourly wind generation grew by over 40 percent from 2011 to 2015. To account for this we regress the hourly indicator of congestion ($Congested_h$) on hourly wind generation, zonal load, fuel prices, SPP load and wind, average temperature, the square of each of the preceding controls, hour-by-month and day-of-week fixed effects, a dummy for 2013 observations (when CREZ was partially completed), and a dummy for 2014 and 2015 observations (when CREZ was essentially completed). The parameter on the year 2014 and 2015 dummy was −0.45, with standard errors of 0.07, suggesting that, after conditioning on market conditions, the probability of being in a congested hour fell by 45 percentage points after CREZ. This conditional decline in congestion from 2011–2012 to 2014–2015 leads to a roughly $227 (OLS) to $366 (IV-LASSO) million dollar increase in the annual environmental value of wind due to increased market integration, based on 2015 averages. The bulk of this increase, 77 percent (IV-LASSO) and 85 percent (OLS), comes from decreased local pollutant damages.

Of course, CREZ may have done more than simply lower the frequency of grid congestion. For instance, CREZ is frequently credited with reducing the frequency and amount of potential wind generation that is curtailed. In 2012, Wiser and Bolinger (2019) report average wind generation curtailment rates of about 4 percent in ERCOT and that rate fell to 1 percent in 2015. If we attribute all of that reduced curtailment to CREZ, then based on 2015 average wind generation values and congestion rates, the environmental value of the reduced curtailment is about $62 million annually, using the main OLS estimate.[30] However, this may be an overestimate as curtailment rates over 2012–2015 may not have dropped exclusively because of CREZ. Prior to any significant CREZ-construction, Wiser and Bolinger (2019) show curtailment rates falling from a high of 17 percent in 2009 to about 8 percent for 2010–2011, then to 4 percent in 2012. Various changes to market rules, as well as year-to-year variation in wind speeds, occur throughout the time span of analysis, which are also likely key determinants of curtailment.

CREZ is also often credited with increasing wind generation capacity. It is true that wind generation capacity did expand quite rapidly after CREZ was completed, with capacity gains of about 4.7 GW from 2013 to 2015. However, over this period, MISO and the Southwest Power Pool, the other ISOs with considerable wind capacity, also added large amounts of wind generating capacities, about 3 GW and 4 GW, respectively. These additions, and likely a large share of the additions in ERCOT, were generally seen as motivated by the desire to complete new wind farms before the federally funded production tax credit was reduced. Thus, while it is interesting and worthwhile to examine the effects of transmission expansion on wind generation capacity additions, such an examination is beyond the scope of this study.

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

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

increases with more renewables on the system.[31] 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, roughly 60 percent of the transmission project was completed during the last half of 2013 (see Figure 5).[32] This relatively short window of substantial transmission expansion gives us an opportunity to run an event study (of sorts) where we can examine how environmental damages differ after versus before the jump in transmission capacity at different levels of wind generation.

The following model is estimated separately for pre- and post-jump samples:

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

where D_{hdmy} is the hourly ERCOT-wide damage, W_{hdmy} is the hourly ERCOT wind generation, and $f_i(X_{hdmy})$ is again a function of control variables that include linear and quadratic specifications of zonal load, SPP load and wind, and the average Texas temperature. We again include hour-by-month (γ_{hm}) and day-of-week (δ_d) fixed effects. We define the year spanning June 30, 2012 through June 30, 2013 as the pre-jump period and January 3, 2014 through January 3, 2015 as the post-jump period. These two sample periods are shown as the shaded regions in Figure 5 and, as can be seen, exclude the roughly six-month period where CREZ progresses from roughly 40 percent to 100 percent completed. As expected, the probability of being a congested hour (as defined for our base specification in the ERCOT analysis) drops considerably from the pre-jump rate of about 48 percent to the post-jump rate of 30 percent.

Using the estimates of equation (13), we predict the pre- and post-jump average hourly environmental damage across a range of wind generation values.[33] Figure 6 displays the predicted pre- and post-jump hourly damages and the corresponding 95 percent confidence intervals. The figure again depicts a complementary relationship between transmission and renewables with respect to environmental damages. With low levels of wind generation, the increased transmission capacity provides little or no environmental value. We might expect this because while transmission may allow less damaging fossil fuel generation in the west to supplant high-damage generation in the east, with low wind values we will also have hours where prices are higher in the west than the east. The increased transmission in these instances promotes a flow of power from east to west, supplied by increased production from higher-damage fossil fuel units located near population centers. Conversely when

[31] This follows from our simple theory model as well. If Q increases, F_e falls and F_w increases in otherwise congested periods. If global emission rates are similar in the regions, but local pollutants cause more damage in the east than the west, increased transmission will reduce environmental damages. Those reductions should be larger in periods with greater wind generation as the wind generation offsets increases in F_w that come with increased Q. Of course, this is predicated on flows being from west to east, which, in practice, is not always the case in ERCOT and MISO.

[32] Figure 5 plots the share of CREZ line-miles completed. We consider a line segment completed on the date the line was energized according to project data provided to us by ERCOT.

[33] Summary statistics and point estimates on each sample are reported in online Appendix Tables B.22 and B.23. For the remaining controls in (13), the prediction of environmental damages are made with these variables at their respective mean values over the two samples combined.

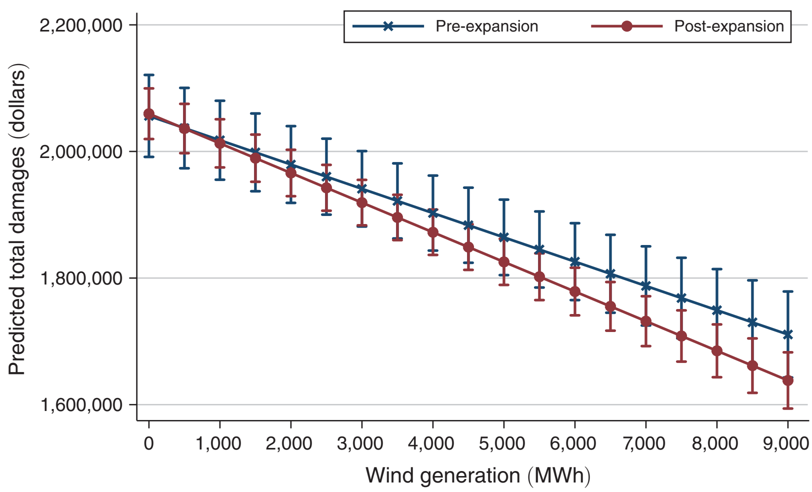

Figure 6. Predicted Environmental Damages in the Pre-/Post-CREZ Jump Samples versus Varying Levels of Wind Generation

wind generation is high, generation flows will typically be from west to east, and increased transmission will facilitate more substitution from high-damage fossil fuel in the east with lower-damage fossil fuel in the west—or even with wind generation itself in the west.[34] Accordingly, we find that the environmental damages are predicted to be lower with high wind in the post-jump period than in the pre-jump period.[35]

V. Conclusion

The growth of renewable electricity resources, particularly wind, has spurred substantial private and public interest in increasing transmission capacity to move electricity from renewable-rich areas to demand centers. While such projects are usually advocated on the grounds of market considerations such as arbitraging regional electricity prices or grid reliability, this paper highlights that these investments in transmission infrastructure also provide sizable nonmarket benefits.

First, we analytically highlight two key channels through which transmission congestion (or alleviation via transmission expansion), can affect the nonmarket value of wind—the emissions level and location effect. The emissions level effect highlights that congestion alters which marginal fossil units respond to wind generation, affecting the level of emissions and damages avoided. The emissions location effect describes how congestion can also change where wind-induced emission reductions occur, affecting damages from local pollutants. While the emissions level

[34] To the extent that wind generation is the marginal generating source in the West zone and power flow from west to east is congested, increased transmission would supplant fossil generation in the east with zero-emission wind generation in the west.

[35] We also considered specifications where wind enters equation (13) as second and third order polynomials. In addition, we considered a prejump sample as the six months before 6/30/2013 and the postjump sample as the six months from 01/03/2014 on. Results from these specifications are qualitatively the same as presented here.

effect has an ambiguous impact on the environmental value of renewables, the emissions location effect likely leads to dramatic increases in the environmental value of renewables following transmission expansions. This stems from the fact that much of the investment in transmission capacity is designed to connect sparsely populated renewable-rich regions with much more heavily populated demand centers. Consequently, transmission expansions enable renewable generation to offset more fossil generation, and thus emissions, from larger population centers—precisely where emissions impose the largest damages.

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

Combining 2011–2015 hourly wind generation and emissions with county-level damages by pollutant, OLS estimates show that during hours when the ERCOT market was congested (transmission capacity constraints were binding) an additional MWh of wind generation reduced total environmental damages from the electric sector by $40. However, during uncongested hours, an additional MWh of wind reduced environmental damages by $52, a 30 percent increase in the nonmarket value of wind. The bulk of this increased value in uncongested periods stems from the emission location effect. Specifically, when the market is uncongested, generation from wind turbines concentrated in the sparsely populated western portion of Texas offsets more generation from high-damage fossil fuel units located near the population centers to the east (e.g., Houston). A similar pattern emerges in MISO; grid congestion reduces the environmental value of wind, as wind generation in western MISO areas such as Iowa and southern Minnesota is unable to offset fossil generation from demand centers in eastern MISO.

Using the estimates from ERCOT, we are able to provide back-of-the-envelope estimates of the nonmarket benefits provided by the CREZ project—a roughly $7 billion investment designed to increase transmission capacity between wind-rich west Texas and demand centers to the east. We estimate that the reduced grid congestion brought about by the CREZ project increased the environmental value of ERCOT's wind generation on the order of $227–366 million annually, similar in magnitude to the market benefits found in LaRiviere and Lu (2017).

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