Online Appendix
Emissions, Transmission, and the Environmental Value of Renewable Energy

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A. ERCOT and the CREZ expansion

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

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

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

or lower – particularly in the high wind, low demand overnight hours.

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

B. Appendix Tables and Figures

TABLE B.1—AVERAGE MARGINAL EFFECT OF WIND GENERATION - ERCOT DONUT CONGESTED

	OLS			
	(1)	(2)	(3)	(4)
Wind	-52.69	-53.37	-54.02	-54.49
	(1.912)	(2.028)	(2.189)	(2.360)
Wind*Congested	12.99	14.54	17.64	21.53
	(2.345)	(2.847)	(3.358)	(4.164)
Congested	-111,617	-1,033	66,667	208,517
	(396,353)	(462,867)	(565,435)	(591,537)
Donut	\$0.5-1.5	\$0.1-5	\$0.01-10	\$0.001-15
N	40,104	31,878	25,730	19,741
R^2	0.917	0.917	0.914	0.911
	IV-LASSO			
	(1)	(2)	(3)	(4)
Wind	-55.11	-56.57	-56.51	-56.33
	(3.065)	(2.977)	(2.747)	(2.708)
Wind*Congested	20.79	27.33	25.52	21.69
	(8.255)	(9.532)	(9.614)	(10.90)
Congested	-125,787	-169,800	-128,643	-37,503
	(56,545)	(63,431)	(63,776)	(68,131)
Donut	\$0.5-1.5	\$0.1-5	\$0.01-10	\$0.001-15
Observations	40,103	31,877	25,729	19,740
R-squared	0.915	0.913	0.912	0.907

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

Table B.2—Average marginal effect of wind generation on emissions - ERCOT

	(1) SO_2 (lbs)	(2) NO_x (lbs)	(3) PM2.5 (lbs)	(4) CO_2 (tons)
Wind	-1.511	-0.571	-0.0551	-0.598
	(0.0929)	(0.0308)	(0.00130)	(0.0116)
Wind*Congested	0.553	-0.0808	0.0102	0.0480
	(0.120)	(0.0473)	(0.00201)	(0.0127)
Congested	-21,309	3,380	-396.5	-1,626
	(16,192)	(4,545)	(203.4)	(1,471)
Hour-Month FE	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y
All controls	Y	Y	Y	Y
Zonal load	Y	Y	Y	Y
Fully interacted	Y	Y	Y	Y
N	43,824	43,824	43,824	43,824
R^2	0.851	0.881	0.965	0.987

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

Table B.3—Average marginal effect of wind generation on emissions - MISO

	(1) SO_2 (lbs)	(2) NO_x (lbs)	(3) PM2.5 (lbs)	(4) CO_2 (tons)
Wind	-2.921	-1.353	-0.131	-0.765
	(0.231)	(0.0621)	(0.00493)	(0.0209)
Wind*Congested	0.420	-0.0353	0.00739	0.0546
	(0.181)	(0.0370)	(0.00444)	(0.0189)
Congested	-60,678	-19,071	269.3	-804.5
	(24,030)	(6,236)	(591.2)	(2,516)
Hour-Month FE	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y
All controls	Y	Y	Y	Y
Zonal load	Y	Y	Y	Y
Fully interacted	Y	Y	Y	Y
N	35,000	35,000	35,000	35,000
R^2	0.936	0.947	0.966	0.978

Note: Coefficient on wind can be interpreted as lbs or tons/MWh. Hour-by-month, month-by-year, day of week fixed effects included. Control variables include linear and quadratic: average gas price/average coal price, state temperature, SPP wind, and load from surrounding areas (SPP, IESO, TVA, PJM). Zonal load includes linear and quadratic controls for 8 MISO zones described in the text. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses.

TABLE B.4—AVERAGE MARGINAL EFFECT OF WIND GENERATION - ERCOT ALTERNATIVE CUTOFFS

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) Total Dmg	(5) Total Dmg
Wind	-54.49	-53.37	-52.68	-51.16	-50.65
	(2.336)	(2.022)	(1.910)	(1.855)	(1.879)
Wind*Congested	9.310	10.42	11.24	12.23	11.82
	(2.309)	(2.256)	(2.125)	(2.225)	(2.445)
Congested	-175,900	-167,321	-215,886	-298,348	-307,969
	(366,406)	(392,027)	(377,701)	(403,193)	(404,259)
Congested cutoff	0	0.1	0.5	3	5
Hour-Month FE	Y	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y	Y
All controls	Y	Y	Y	Y	Y
Zonal load	Y	Y	Y	Y	Y
Fully interacted	Y	Y	Y	Y	Y
N	43,824	43,824	43,824	43,824	43,824
R^2	0.918	0.919	0.919	0.918	0.918

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

TABLE B.5—AVERAGE MARGINAL EFFECT OF WIND GENERATION ON ENVIRONMENTAL DAMAGES - MISO WITH $c = 8$

	(1)	(2)	(3)	(4)	(5)
Wind	-61.95	-79.98	-78.77	-84.53	-85.81
	(8.515)	(3.902)	(3.699)	(4.056)	(3.800)
Wind*Congested	-25.46	8.885	6.896	9.453	11.91
	(8.771)	(3.461)	(3.246)	(3.574)	(3.563)
Congested	166,340	-59,484	-60,941	-72,545	-1.290e+06
	(40,199)	(18,596)	(15,688)	(15,859)	(624,147)
Load		155.8	81.50		
		(12.41)	(16.11)		
Load^2		-0.0005	-0.0001		
		(0.0001)	(0.0001)		
Fuelratio		3.334e+07	2.727e+07	2.918e+07	3.504e+07
		(1.031e+07)	(9.203e+06)	(1.180e+07)	(1.361e+07)
Fuelratio^2		-1.914e+08	-1.622e+08	-1.713e+08	-2.052e+08
		(5.821e+07)	(5.194e+07)	(6.824e+07)	(8.135e+07)
Add'l controls	N	N	Y	Y	Y
Zonal load	N	N	N	Y	Y
Fully interacted	N	N	N	N	Y
N	43,824	43,824	43,744	35,000	35,000
R^2	0.848	0.954	0.959	0.950	0.952

Note: All specifications include hour-month, month-year, and day-of-week fixed effects. Coefficient on wind can be interpreted as $/MWh. Load is the northern MISO-wide load. Fuelratio is average gas price/average coal price. Additional controls include linear and quadratic temperature and load from surrounding areas (SPP, IESO, TVA, PJM). Zonal load includes linear and quadratic controls for 8 MISO zones described in the text. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses.

TABLE B.6—AVERAGE MARGINAL EFFECT OF WIND GENERATION ON ENVIRONMENTAL DAMAGES - MISO WITH $c = 2$

	(1)	(2)	(3)	(4)	(5)
Wind	-47.63	-81.86	-79.02	-86.45	-89.43
	(14.21)	(5.688)	(5.665)	(6.501)	(5.683)
Wind*Congested	-32.79	6.967	3.749	6.891	11.09
	(12.42)	(4.474)	(4.418)	(5.119)	(4.547)
Congested	175,572	-40,914	-38,628	-46,021	-732,522
	(40,376)	(18,059)	(16,427)	(16,611)	(565,351)
Load		156.5	82.62		
		(12.30)	(16.07)		
$Load^2$		-0.0005	-0.0002		
		(0.0001)	(0.0001)		
Fuelratio		3.328e+07	2.719e+07	2.915e+07	4.687e+07
		(1.032e+07)	(9.205e+06)	(1.179e+07)	(1.471e+07)
$Fuelratio^2$		-1.912e+08	-1.617e+08	-1.712e+08	-2.784e+08
		(5.835e+07)	(5.206e+07)	(6.832e+07)	(8.768e+07)
Add'l controls	N	N	Y	Y	Y
Zonal load	N	N	N	Y	Y
Fully interacted	N	N	N	N	Y
N	43,824	43,824	43,744	35,000	35,000
R^2	0.848	0.954	0.959	0.950	0.952

Note: All specifications include hour-month, month-year, and day-of-week fixed effects. Coefficient on wind can be interpreted as $/MWh. Load is the northern MISO-wide load. Fuelratio is average gas price/average coal price. Additional controls include linear and quadratic temperature and load from surrounding areas (SPP, IESO, TVA, PJM). Zonal load includes linear and quadratic controls for 8 MISO zones described in the text. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses.

TABLE B.7—AVERAGE MARGINAL EFFECT OF WIND GENERATION - ERCOT CONTINUOUS TREATMENT

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) Total Dmg	(5) Total Dmg
Wind	-47.19	-46.39	-48.99	-48.62	-49.83
	(3.321)	(1.502)	(1.880)	(1.843)	(1.881)
Wind*Congested	0.200	0.0823	0.0661	0.0465	0.332
	(0.0733)	(0.0393)	(0.0367)	(0.0347)	(0.0723)
Congested	-92.35	-469.4	-419.6	-295.5	9,749
	(177.0)	(132.8)	(126.2)	(110.6)	(9,939)
Hour-Month FE	Y	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y	Y
Add'l controls	N	N	Y	Y	Y
Zonal load	N	N	N	Y	Y
Fully interacted	N	N	N	N	Y
N	43,824	43,824	43,824	43,824	43,824
R^2	0.915	0.916	0.916	0.915	0.915

Note: Coefficient on wind can be interpreted as $/MWh. Congested is defined as the average price spread of the 6 zonal pairwise differences. Hour-by-month, month-by-year, day of week fixed effects included. With the exception of column 1, control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses.

TABLE B.8—AVERAGE MARGINAL EFFECT OF WIND GENERATION - ERCOT BINNED TREATMENT

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) Total Dmg
Wind	-53.92	-53.80	-56.26	-54.65
	(3.733)	(2.108)	(2.231)	(2.152)
Wind*Cong01	-0.0714	6.462	6.524	5.347
	(2.843)	(1.835)	(1.722)	(1.638)
Wind*Cong15	9.392	14.21	14.16	12.15
	(3.976)	(2.343)	(2.285)	(2.100)
Wind*Cong510	9.135	14.88	14.33	12.03
	(4.263)	(3.032)	(2.841)	(2.664)
Wind*Cong1020	16.86	18.49	17.64	14.70
	(5.331)	(3.897)	(3.514)	(3.324)
Wind*Cong20+	18.99	14.86	13.72	10.57
	(7.078)	(4.469)	(4.395)	(4.285)
Cong01	57,726	-13,432	-13,270	-12,668
	(15,896)	(8,187)	(7,738)	(7,475)
Cong15	33,907	-56,519	-53,363	-47,665
	(23,616)	(11,589)	(11,233)	(10,599)
Cong510	5,291	-77,129	-73,936	-65,888
	(20,575)	(13,763)	(13,085)	(12,714)
Cong1020	7,479	-76,476	-72,395	-61,929
	(26,546)	(15,456)	(14,244)	(13,649)
Cong20u+	33,150	-73,291	-69,002	-56,586
	(26,535)	(16,772)	(16,584)	(15,847)
Hour-Month FE	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y
Add'l controls	N	N	Y	Y
Zonal load	N	N	N	Y
Fully interacted	N	N	N	N
Observations	43,824	43,824	43,824	43,824
R-squared	0.820	0.912	0.914	0.916

Note: Coefficient on wind can be interpreted as $/MWh. Congested variable is binned according to average price spread of the 6 zonal pairwise differences - (e.g. Cong510 = 1 if the average price spread is above $5 but below $10) Hour-by-month, month-by-year, day of week fixed effects included in all specification. Control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Cluster robust standard errors at month-by-year in parentheses.

TABLE B.9—AVERAGE MARGINAL EFFECT OF WIND GENERATION - ERCOT ZONAL CONGESTION DEFINTION

	(1) Total Dmg	(2) Local Dmg	(3) CO_2 Dmg
Wind	-51.71	-30.02	-21.69
	(1.840)	(1.660)	(0.407)
Wind*CongNorth	-3.143	-2.975	-0.168
	(2.814)	(2.545)	(0.479)
Wind*CongSouth	6.624	5.606	1.018
	(2.336)	(2.104)	(0.499)
Wind*CongHouston	6.144	5.730	0.414
	(2.250)	(2.083)	(0.496)
CongNorth	4,739	7,752	-3,013
	(13,484)	(12,155)	(2,701)
CongSouth	-21,416	-14,619	-6,798
	(12,849)	(11,510)	(2,692)
CongHouston	-28,016	-28,696	679.1
	(11,712)	(10,869)	(2,436)
Hour-Month FE	Y	Y	Y
Month-Year FE	Y	Y	Y
DOW FE	Y	Y	Y
All controls	Y	Y	Y
Zonal load	Y	Y	Y
Fully Interacted	Y	Y	Y
N	43,824	43,824	43,824
R^2	0.919	0.822	0.985

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

TABLE B.10—AVERAGE MARGINAL EFFECT OF WIND GENERATION - ERCOT PAIRWISE CONGESTION DEFINITION

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) Total Dmg	(5) Total Dmg	(6) Total Dmg
Wind	-51.96	-50.92	-51.88	-50.19	-51.24	-51.32
	(1.894)	(1.854)	(1.802)	(1.824)	(1.833)	(1.874)
Wind*Congested	10.13	10.40	11.82	14.44	11.88	13.92
	(2.193)	(2.679)	(2.289)	(3.027)	(2.417)	(2.341)
Congested	-448,881	-383,234	-131,569	-420,613	-548,890	-374,105
	(362,398)	(403,412)	(402,921)	(409,393)	(356,138)	(371,780)
Congested	W-S	W-N	W-H	N-H	N-S	H-S
Hour-Month FE	Y	Y	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y	Y	Y
All controls	Y	Y	Y	Y	Y	Y
Zonal load	Y	Y	Y	Y	Y	Y
Fully interacted	Y	Y	Y	Y	Y	Y
N	43,824	43,824	43,824	43,824	43,824	43,824
R-squared	0.919	0.918	0.919	0.918	0.919	0.919

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

Table B.11—Average marginal effect of wind generation - ERCOT West congestion definition

	(1) Total Dmg	(2) Local Dmg	(3) CO_2 Dmg	(4) Total Dmg	(5) Local Dmg	(6) CO_2 Dmg
Wind	-52.23	-30.44	-21.79	-51.55	-29.78	-21.77
	(1.847)	(1.655)	(0.422)	(1.845)	(1.657)	(0.405)
Wind*Congested	11.73	10.10	1.622	11.53	9.831	1.702
	(2.241)	(1.995)	(0.461)	(2.451)	(2.187)	(0.501)
Congested	-151,750	-81,919	-69,831	-408,800	-311,061	-97,738
	(395,573)	(353,769)	(60,754)	(398,615)	(352,104)	(63,079)
Cutoff	$1	$1	$1	$2	$2	$2
Hour-Month FE	Y	Y	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y	Y	Y
All controls	Y	Y	Y	Y	Y	Y
Zonal load	Y	Y	Y	Y	Y	Y
Fully interacted	Y	Y	Y	Y	Y	Y
N	43,824	43,824	43,824	43,824	43,824	43,824
R-squared	0.919	0.822	0.985	0.918	0.820	0.985

Note: Coefficient on wind can be interpreted as $/MWh. Congested = 1 if average price spread between West and other three regions a) exceeds $1 (columns 1-3) and b) exceeds $2 (columns 4-6). Hour-by-month, month-by-year, day of week fixed effects included. Control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses.

Table B.12—Average marginal effect of wind generation - ERCOT daily aggregation

	(1) Total Dmg	(2) Local Dmg	(3) CO_2 Dmg
Wind	-46.85	-25.51	-21.34
	(3.501)	(3.147)	(0.802)
Wind*Congested	13.08	10.89	2.186
	(5.016)	(4.498)	(0.943)
Congested	-1.959e+06	-1.619e+06	-340,726
	(633,270)	(556,253)	(140,498)
Month-Year FE	Y	Y	Y
DOW FE	Y	Y	Y
All controls	Y	Y	Y
Zonal load	Y	Y	Y
N	1,826	1,826	1,826
R^2	0.920	0.832	0.985

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

Table B.13—Average marginal effect of wind generation - MISO daily aggregation

	(1) Total Dmg	(2) Local Dmg	(3) CO_2 Dmg
Wind	-80.98	-50.73	-30.25
	(8.992)	(8.203)	(1.557)
Wind*Congested	6.563	2.955	3.609
	(10.12)	(9.288)	(2.012)
Congested	-1.999e+06	-1.315e+06	-684,832
	(1.243e+06)	(1.133e+06)	(229,423)
Month-Year FE	Y	Y	Y
DOW FE	Y	Y	Y
All controls	Y	Y	Y
Zonal load	N	N	N
N	1,826	1,826	1,826
R^2	0.968	0.959	0.980

Note: Coefficient on wind can be interpreted as $/MWh. Congested is the average number of Congested hours in a given day. Month-by-year, day of week fixed effects included for all specifications. Control variables include linear and quadratic: load, average gas price/average coal price, state temperature, SPP wind and load from surrounding areas (SPP, IESO, TVA, PJM). Cluster robust standard errors at month-by-year in parentheses.

Table B.14—Average marginal effect of wind generation on environmental damages by year-ERCOT

	2011 Total Dmg	2012 Total Dmg	2013 Total Dmg	2014 Total Dmg	2015 Total Dmg
Wind	-67.77	-54.03	-46.40	-50.13	-50.74
	(4.635)	(5.495)	(4.443)	(3.414)	(2.748)
Wind*Congested	24.20	11.19	13.68	13.19	10.09
	(5.491)	(5.243)	(4.316)	(4.210)	(3.140)
Congested	1.156e+06	1.644e+06	3.431e+06	248,727	-2.156e+06
	(761,484)	(690,014)	(2.016e+06)	(876,637)	(1.167e+06)
N	8,760	8,784	8,760	8,760	8,760
R^2	0.929	0.916	0.902	0.920	0.947

Note: Coefficient on wind can be interpreted as $/MWh. Congested = 1 if average price spread > 1. 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 day of year in parentheses.

TABLE B.15—AVERAGE MARGINAL EFFECT OF WIND GENERATION ON ENVIRONMENTAL DAMAGES BY YEAR-MISO

	2011	2012	2013	2014
	Total Dmg	Total Dmg	Total Dmg	Total Dmg
Wind	-90.78	-100.8	-92.41	-80.50
	(3.335)	(2.480)	(2.665)	(2.978)
Wind*Congested	-1.520	15.22	8.177	18.02
	(4.392)	(3.129)	(3.239)	(3.573)
Congested	-3.387e+06	-4.351e+06	-1.154e+07	-396,949
	(677,905)	(442,072)	(718,222)	(612,197)
N	8,737	8,778	8,740	8,745
R^2	0.960	0.960	0.932	0.956

Note: Coefficient on wind can be interpreted as $/MWh. Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Additional controls include linear and quadratic temperature and load from surrounding areas (SPP, IESO, TVA, PJM). Zonal load includes linear and quadratic controls for 8 MISO zones described in the text. All specifications are fully interacted models, which interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at day of year in parentheses.

TABLE B.16—AVERAGE MARGINAL EFFECT OF WIND GENERATION - ERCOT SHOULDER VS NON-SHOULDER

	(1)	(2)	(3)
Panel A: Shoulder months			
	Total Dmg	Local Dmg	CO_2 Dmg
Wind	-52.84	-30.84	-22.00
	(2.742)	(2.315)	(0.859)
Wind*Congested	10.94	9.205	1.734
	(2.770)	(2.499)	(0.727)
Congested	418,878	479,025	-60,147
	(736,342)	(654,862)	(113,431)
N	14,640	14,640	14,640
R^2	0.838	0.712	0.960
Panel B: Non-shoulder months			
	Total Dmg	Local Dmg	CO_2 Dmg
Wind	-52.23	-30.39	-21.85
	(2.577)	(2.340)	(0.444)
Wind*Congested	13.44	11.59	1.849
	(3.123)	(2.707)	(0.592)
Congested	-411,271	-337,252	-74,018
	(478,827)	(429,525)	(74,671)
N	29,184	29,184	29,184
R^2	0.929	0.847	0.987
All controls	Y	Y	Y
Zonal load	Y	Y	Y
Fully interacted	Y	Y	Y

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

TABLE B.17—AVERAGE MARGINAL EFFECT OF WIND GENERATION - MISO SHOULDER VS NON-SHOULDER

	(1)	(2)	(3)
Panel A: Shoulder months			
	Total Dmg	Local Dmg	CO_2 Dmg
Wind	-93.13	-63.99	-29.14
	(2.333)	(2.101)	(0.442)
Wind*Congested	13.06	11.39	1.671
	(2.785)	(2.517)	(0.529)
Congested	-1.453e+06	-1.219e+06	-234,172
	(647,368)	(576,124)	(132,206)
N	11,697	11,697	11,697
R^2	0.931	0.906	0.962
Panel B: Non-shoulder months			
	Total Dmg	Local Dmg	CO_2 Dmg
Wind	-87.45	-57.31	-30.14
	(1.793)	(1.633)	(0.310)
Wind*Congested	14.41	11.73	2.682
	(2.315)	(2.090)	(0.407)
Congested	-863,382	-807,897	-55,485
	(341,090)	(307,201)	(60,293)
N	23,303	23,303	23,303
R^2	0.954	0.936	0.980
All controls	Y	Y	Y
Zonal load	Y	Y	Y
Fully interacted	Y	Y	Y

Note: Coefficient on wind can be interpreted as $/MWh. Shoulder months are March, April, October, November. Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Additional controls include linear and quadratic temperature and load from surrounding areas (SPP, IESO, TVA, PJM). Zonal load includes linear and quadratic controls for 8 MISO zones described in the text. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses.

TABLE B.18—AVERAGE MARGINAL EFFECT OF WIND GENERATION ON CONGESTED - ERCOT

	(1) Congested	(2) Congested	(3) Congested	(4) Congested
Wind	4.47e-05	4.46e-05	4.74e-05	4.65e-05
	(6.38e-06)	(6.28e-06)	(6.57e-06)	(6.63e-06)
Load		1.17e-05	1.05e-05	
		(7.06e-06)	(8.97e-06)	
$Load^2$		5.87e-11	9.14e-11	
		(8.44e-11)	(1.02e-10)	
Fuelratio		-26.73	-23.52	-21.34
		(17.04)	(17.89)	(17.75)
$Fuelratio^2$		648.3	575.1	511.1
		(236.4)	(245.6)	(244.6)
Hour-Month FE	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y
Add'l controls	N	N	Y	Y
Zonal load	N	N	N	Y
N	43,824	43,824	43,824	43,824
R^2	0.252	0.271	0.273	0.279

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

Table B.19—Average marginal effect of wind generation on Congested - MISO

	(1) Congested	(2) Congested	(3) Congested	(4) Congested
Wind	8.43e-05	8.34e-05	7.92e-05	8.35e-05
	(3.45e-06)	(3.52e-06)	(3.39e-06)	(4.31e-06)
Load		-4.55e-06	1.45e-05	
		(7.69e-06)	(1.04e-05)	
Load^2		1.02e-10	-0	
		(5.78e-11)	(7.23e-11)	
Fuelratio		8.136	8.954	1.441
		(4.580)	(5.062)	(3.452)
Fuelratio^2		-50.41	-48.31	-4.379
		(28.48)	(31.19)	(21.67)
Hour-Month FE	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y
Add'l controls	N	N	Y	Y
Zonal load	N	N	N	Y
N	43,824	43,824	43,744	35,000
R^2	0.230	0.238	0.258	0.255

Note: Coefficient on wind can be interpreted as the effect of wind on the probability that MISO markets are congested. Load is MISO-wide load. Fuelratio is average gas price/average coal price. Hour-by-month, month-by-year, day of week fixed effects included for all specifications. Additional controls include linear and quadratic state temperature, SPP wind, and load from surrounding areas (SPP, IESO, TVA, PJM). Zonal load includes linear and quadratic controls for 8 MISO zones described in the text. Cluster robust standard errors at month-by-year in parentheses.

Table B.20—Average marginal effect of wind generation - ERCOT SO_2, NO_X, CO_2 only

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) Total Dmg	(5) Total Dmg
Wind	-49.35	-48.04	-50.35	-49.43	-49.93
	(3.172)	(1.601)	(1.850)	(1.770)	(1.830)
Wind*Congested	8.885	11.91	11.46	9.637	12.12
	(2.832)	(2.059)	(1.930)	(1.748)	(2.207)
Congested	1,236	-61,064	-57,820	-49,603	-238,089
	(14,985)	(9,345)	(8,996)	(8,288)	(373,712)
Hour-Month FE	Y	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y	Y
Add'l controls	N	N	Y	Y	Y
Zonal load	N	N	N	Y	Y
Fully interacted	N	N	N	N	Y
Observations	43,824	43,824	43,824	43,824	43,824
R-squared	0.815	0.908	0.910	0.912	0.915

Note: Coefficient on wind can be interpreted as \$/MWh. Total damages include SO_2, NO_X, CO_2 and exclude PM2.5. Congested = 1 if average price spread > 1 (38% of obs). With the exception of column 1, control variables include linear and quadratic: average gas price/average coal price, temperature, SPP wind and SPP load. Zonal load includes linear and quadratic controls for ERCOT West, North, South and Houston load. Fully interacted model interacts all controls (including fixed effects) with Congested variable. Cluster robust standard errors at month-by-year in parentheses.

TABLE B.21—AVERAGE MARGINAL EFFECT OF WIND GENERATION - ERCOT MATCHED SAMPLE

	(1) Total Dmg	(2) Total Dmg	(3) Total Dmg	(4) Total Dmg
Wind	-52.47	-52.40	-53.00	-52.20
	(1.899)	(1.911)	(2.038)	(2.070)
Wind*Congested	12.51	11.22	8.026	6.773
	(2.252)	(2.102)	(2.373)	(2.326)
Congested	-153,670	-220,794	-242,664	-402,179
	(396,457)	(399,873)	(374,929)	(349,198)
Hour-Month FE	Y	Y	Y	Y
Month-Year FE	Y	Y	Y	Y
DOW FE	Y	Y	Y	Y
All controls	Y	Y	Y	Y
Zonal load	Y	Y	Y	Y
Fully interacted	Y	Y	Y	Y
N	43,801	42,606	27,953	19,338
R^2	0.919	0.915	0.906	0.913

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

TABLE B.22—EVENT STUDY SUMMARY STATISTICS

	Pre-Expansion			
	Mean	SD	Min	Max
Damages ($)	1,824,654	402,921	758,120	2,914,861
Wind (MWh)	3,774	2,326	8	9,542
Congested	0.476	0.499	0	1
Load_{North} (MWh)	14,068	3,744	8,159	27,556
Load_{South}(MWh)	10,022	2,552	5,955	17,977
Load_{West}(MWh)	2,876	437	2,139	4,414
Load_{Houst}(MWh)	9,970	2,376	6,162	17,373
Fuel Price Ratio	0.015	0.002	0.011	0.020
	Post-Expansion			
	Mean	SD	Min	Max
Damages ($)	1,856,711	439,676	768,490	2,988,823
Wind (MWh)	4,098	2,574	14	10,844
Congested	0.297	0.457	0	1
Load_{North}(MWh)	14,517	3,602	8,399	25,955
Load_{South}(MWh)	10,562	2,645	5,972	18,168
Load_{West}(MWh)	3,364	447	2,530	4,781
Load_{Houst}(MWh)	10,396	2,313	6,625	17,772
Fuel Price Ratio	0.019	0.004	0.011	0.053

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

Table B.23—Pre- vs Post-Expansion Estimates

	Pre	Post
Wind	-38.31	-46.43
	(3.302)	(2.435)
Load_{Houst}	28.59	45.21
	(53.16)	(38.93)
Load^2_{Houst}	-0.000137	-0.000183
	(0.00211)	(0.00156)
Load_{North}	122.1	133.2
	(29.92)	(23.59)
Load^2_{North}	-0.00240	-0.00291
	(0.000802)	(0.000674)
Load_{South}	52.92	87.52
	(53.46)	(32.44)
Load^2_{South}	-0.000358	-0.00301
	(0.00219)	(0.00123)
Load_{West}	-551.9	124.5
	(337.8)	(265.1)
Load^2_{West}	0.0753	-0.0163
	(0.0506)	(0.0365)
Constant	-257,615	-603,677
	(657,996)	(373,480)
Observations	8,760	8,760
R-squared	0.866	0.913

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

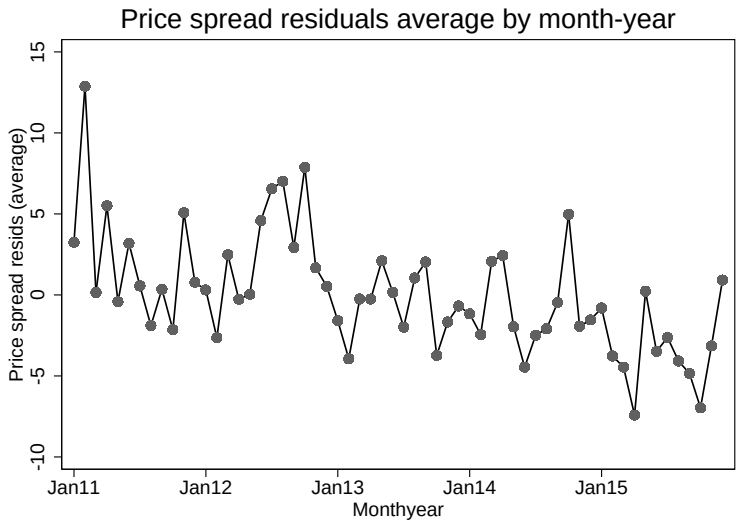

FIGURE B.1. TIME SERIES VARIATION IN AVERAGE PRICE SPREADS (DEMEANED BY HOUR-MONTH) IN ERCOT.

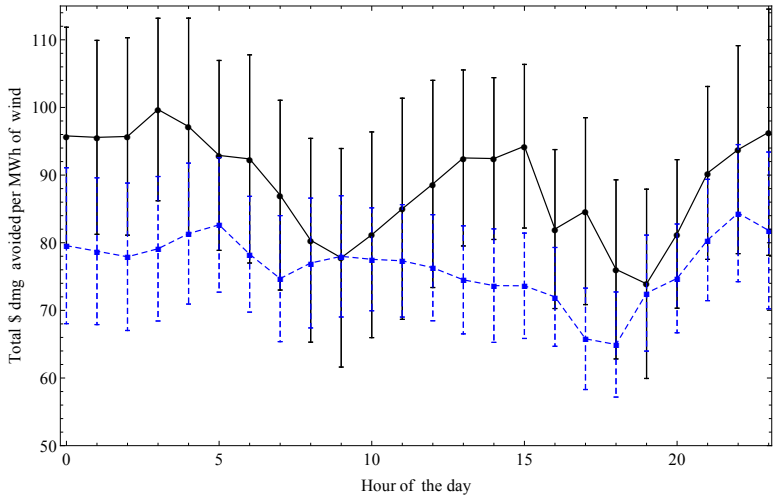

FIGURE B.2. ENVIRONMENTAL VALUE OF WIND BY HOUR IN UNCONGESTED (SOLID) AND CONGESTED PERIODS (DASHED) IN MISO.

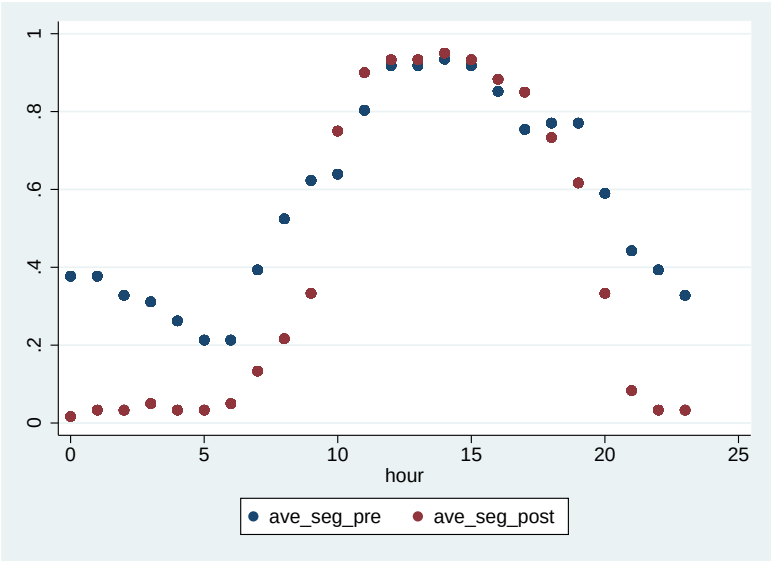

FIGURE B.3. PERCENT OF HOURS THAT ARE CONGESTED IN THE TWO MONTHS PRE- AND POST- MAJOR CREZ PROJECT COMPLETION ON JUNE 30, 2013.