The Fall of Coal: Joint Impacts of Fuel Prices and Renewables on Generation and Emissions

Harrison Fell and Daniel T Kaffine

Online Appendix

A Two-step Panel Selection Model

A.1 Method

In addition to the censored quantile approach, we also use a variation of the Heckman two-step estimation approach (also referred to as a Tobit Type II model or a probit selection model), adapted to accommodate fixed effects in "large T" panel data sets, as described in Fernández-Val and Vella (2011). The method of Fernández-Val and Vella (2011) still has the traditional selection step estimation and intensity step estimation. The selection step estimation used here is the same panel probit model described in equation (3) that models the unit's binary decision to have positive net generation or positive emissions. To estimate the second-step intensity equation, we first need to recover the inverse Mills ratio (IMR), λ_{it}, from the selection step using the bias correction model described in Fernández-Val and Vella (2011).

With an estimate of the IMR, $\hat{\lambda}_{it}$, we estimate the intensity equation given in equation (4) for observations with $y_{it} > 0$. Note this formulation of the selection equation and intensity equation allows for the selection step to be partially determined by variables that are excluded

from the intensity equation, namely the lagged load variables L_{it-l}. This exclusion restriction aids in the identification of the parameters in the intensity equation.[23] From the estimation of the intensity equation, with the IMR included, we can derive average marginal effects of wind generation and the input price ratios on capacity factors and emissions per unit capacity. However, the formation of counterfactual marginal effects as we did using the quantile method is not straightforward given the presence of the IMR and propensity score in the marginal effect (see below).

Beyond obtaining an estimate of the average marginal effect on the intensive margin, the Heckman two-step method is also useful for estimating a counterfactual capacity factor and emissions per unit capacity measure, inclusive of the extensive and intensive margin responses, which allows us to isolate the impacts of higher wind generation and lower gas prices on the observed changes in our dependent variables over time. As explained in the text above, we use equation 7 to form our counterfactual estimates of the expected dependent variable. We can also use equation 7 to decompose the predicted change in the dependent variable given changes in wind generation and/or input price ratios into changes due to "extensive" margin responses and changes due to "intensive" margin responses. More specifically, for a given observation we estimate the change in the expected dependent variable Y_{it} relative to the 2008 year baseline level due to extensive margin responses as:

$$\Delta Y_{it}^{EXT}(\mathbf{X}_{it}, \mathbf{Z}_{it}, \bar{P}_{2013}^{R}, \bar{W}_{2013}) = \left[\Phi\left(\mathbf{Z}_{it}\alpha\right) - \Phi\left(\bar{P}_{2013}^{R}, \bar{W}_{2013}\right)\right]\left[\mathbf{X}_{it}\beta + \rho\lambda_{it}\right]. \tag{8}$$

In this specification, $\bar{P}_{2013}^{R}$ and $\bar{W}_{2013}$ are the 2013 average values of P^R and W, as defined

[23] Tables A.6 and A.7 below examine additional specifications to ensure that the exclusion restriction is not violated by ramping behavior by coal plants.

above, and $\Phi\left(\bar{P}^R_{2013}, \bar{W}_{2013}\right)$ is an estimate of the probability that observation it has a positive Y value given that the P^R and/or W values for it have been replaced by$\bar{P}^R_{2013}$ and/or $\bar{W}_{2013}$, but all other values remained at their 2008 values. Thus, equation 9 reflects the change in Y due to wind and/or price-ratio impacts on the probability that the given unit will be on or off.

Similarly, we estimate the changes due to intensive margin responses as:

$$\Delta Y^{INT}_{it}(\mathbf{X}_{it}, \mathbf{Z}_{it}, \bar{P}^R_{2013}, \bar{W}_{2013}) = \Phi\left(\mathbf{Z}_{it}\alpha\right)\left[\mathbf{X}_{it}\beta + \rho\lambda_{it} - \mathbf{X}_{it}\left(\bar{P}^R_{2013}, \bar{W}_{2013}\right)\beta - \rho\lambda_{it}\left(\bar{P}^R_{2013}, \bar{W}_{2013}\right)\right], \tag{9}$$

where $\mathbf{X}_{it}\left(\bar{P}^R_{2013}, \bar{W}_{2013}\right)$ is the $\mathbf{X}$ matrix of observables for 2008 observations where all price ratio and wind generation values have been replaced with the 2013 averages and $\lambda_{it}\left(\bar{P}^R_{2013}, \bar{W}_{2013}\right)$ is an estimate of the 2008 IMR but using $\bar{P}^R_{2013}$ and $\bar{W}_{2013}$ values in place of the observed 2008 P^R and W values.[24] The percent of the total expected change due to the extensive margin response quoted in footnote 38 above is based on calculating equation 8 for every observation in 2008, averaging those predicted changes, and then taking that average and dividing by the average total predicted change as described above. A similar procedure is used to derive the percent of the total predicted change due to the intensive margin but using equation 9.[25]

[24]Note that we cannot derive bias corrected versions of the counterfactual IMR's, so $\lambda_{it}\left(\bar{P}^R_{2013}, \bar{W}_{2013}\right)$ is based on the uncorrected probit model estimates. Given the large sample size in this application, the bias correction tends to be rather small so this omission is likely not a substantial problem.

[25]Note that the predicted average changes from the extensive portion and intensive portion do not exactly add up to the predicted overall average change. This is likely due to the fact that the predicted overall average change is relative to an observed actual average value for the given dependent variable. By contrast, equations 8 and 9 are changes relative to a predicted 2008 value. Despite this, the differences in the summed predicted changes from the intensive and extensive portions relative to the predicted overall change is quite small in each region, with the largest difference being only four percent of the predicted total change.

A.2 Two-step results

The first stage estimation of the discrete choice model on whether to run the unit or not on a given day is the same as in the quantile-censored model, with results in Tables A.1 and A.2. Results from these estimations provide the basis for the IMR in the two-step estimation approach. The results from the discrete choice model show that lagged load, which serves as the exclusion restriction in the two-step method, is significant across both dependent variables and across all regions.

Parameter estimates from the second-step intensity equation given in (4) are shown in Tables A.3 and A.4. For the specification with capacity factor as the dependent variable, we again find ERCOT, PJM and SPP regions have a negative interaction effect between wind generation and the coal-to-natural gas price ratio, which is statistically significant for ERCOT and SPP. This again confirms the presence of a gas-wind interaction whereby higher wind generation levels will make coal-fired generation more responsive to P^R and vice-versa. For the specification with CO_2 emissions per unit of capacity, the parameter estimates again show an interaction effect that is negative in the same regions, though it is only statistically significant in ERCOT.

We again calculate the marginal effects, however this calculation is slightly more complicated given P^R and W appear in both the selection and intensity equations. The marginal effects are now:

$$\frac{\partial y_{it}}{\partial P_{it}^R} = \beta_1 + 2\beta_2 P_{it}^R + 3\beta_3 \left(P_{it}^R\right)^2 + \beta_7 W_t - \left(\gamma_1 + 2\gamma_2 P_{it}^R + 3\gamma_3 \left(P_{it}^R\right)^2 + \gamma_7 W_t\right) \theta \delta_{it} \quad (10)$$

$$\frac{\partial y_{it}}{\partial W_t} = \beta_4 + 2\beta_5 W_t + 3\beta_6 W_t^2 + \beta_7 P_{it}^R - \left(\gamma_4 + 2\gamma_5 W_t + 3\gamma_6 W_t^2 + \gamma_7 P_{it}^R\right)\theta\delta_{it} \qquad (11)$$

where $\delta_{it} = \lambda_{it}^2 - \pi_{it}\lambda_{it}$ and π_{it} is the propensity score associated with unit i running on day t. To calculate these marginal effects we use the estimated parameters along with the estimated IMR ($\hat{\lambda}_{it}$) and propensity score ($\hat{\pi}_{it}$) values. Because the marginal effects are a function of the estimated propensity score and IMR, one cannot readily form "counterfactual" marginal effects. We instead present 2008 and 2013 marginal effects for each region in Table A.5, where the "2008" marginal effects are evaluated at the 2008 averages for all variables, including the IMR and propensity scores, in equations (10) and (11). Likewise, the "2013" marginal effects are based on using the 2013 averages for all variables.

The upper half of Table A.5 shows the marginal effects of CF with respect to P^R and W. These marginal effects generally follow the pattern of the median quantile regression estimates, with the magnitude of marginal effects increasing from 2008 to 2013. Furthermore, they are also quite similar in magnitude to the corresponding median quantile marginal effects. The bottom half of Table A.5 reports the marginal effects for CO_2 emissions per unit of capacity. Again, these results generally follow the pattern of their counterparts in the median quantile marginal effects, though the differences between the 2008 to 2013 effects are slightly narrower under the two-step approach. The notable exception is in PJM, where 2013 marginal effects are smaller than in 2008. As discussed in the main text, this likely reflects technical constraints on minimum capacity factors that a plant can run at without shutting down.

Overall, the results from the Heckman two-step method provide further evidence of the robustness of our general finding of a significant interaction effect, as well as to the approx-

imate size of this effect.

Table A.1: Capacity Factor Results - Probit Model

	ERCOT	MISO	PJM	SPP
P^R	1.690	1.208	-0.938	0.232
	(0.420)	(0.141)	(0.050)	(0.268)
$\left(P^R\right)^2$	-3.567	-2.750	0.139	-0.570
	(0.486)	(0.176)	(0.025)	(0.377)
$\left(P^R\right)^3$	1.280	1.032	-0.003	0.220
	(0.169)	(0.068)	(0.002)	(0.162)
W	-0.175	-0.100	-0.072	0.118
	(0.166)	(0.052)	(0.104)	(0.149)
W^2	0.193	-0.028	0.809	0.392
	(0.201)	(0.063)	(0.265)	(0.271)
W^3	-0.040	0.013	-0.317	-0.246
	(0.070)	(0.022)	(0.200)	(0.141)
$P^R W$	-0.142	0.086	-0.632	-0.554
	(0.100)	(0.029)	(0.054)	(0.112)
$Load_t$	0.008	0.011	0.006	0.033
	(0.001)	(0.001)	(3.75E-04)	(0.002)
$Load_t^2$	-8.83E-06	-6.54E-06	-5.06E-06	-1.16E-04
	(1.40E-06)	(9.85E-07)	(5.01E-07)	(7.59E-06)
$Load_{t-1}$	5.43E-05	0.085	-0.094	0.001
	(0.001)	(0.029)	(0.020)	(0.002)
$Load_{t-2}$	0.001	-4.95E-06	2.56E-04	0.003
	(0.001)	(0.001)	(2.35E-04)	(0.002)
$Load_{t-3}$	6.85E-04	7.86E-04	-1.78E-05	0.002
	(0.001)	(0.001)	(2.52E-04)	(0.002)
$Load_{t-4}$	-2.49E-05	5.19E-04	-2.80E-04	5.93E-04
	(0.001)	(0.001)	(2.51E-04)	(0.002)
$Load_{t-5}$	0.002	-3.70E-06	-7.03E-05	0.005
	(3.79E-04)	(5.61E-04)	(2.35E-04)	(0.001)
Obs	60,755	416,562	357,825	143,034
N	30	195	171	68
F-stat	153.11	46.74	377.13	141.03

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The dependent variable for all regions is a binary variable equal to one if daily capacity factor is positive and zero otherwise. "Obs" gives total number of observations, "N" denotes number of cross-sectional units included, and "F-stat" gives the F-statistic of the hypothesis that the lagged load variables ($Load_{t-1}$ through $Load_{t-5}$) are jointly equal to zero. The $p-value$ for each F-stat is less that 0.001. Standard errors (SEs) are given in parentheses. SEs are clustered at the unit level. All specifications include unit-level and season-by-year fixed effects.

Table A.2: CO_2 Emission Results - Probit Model

	ERCOT	MISO	PJM	SPP
P^R	1.755	1.213	-0.691	0.293
	(0.432)	(0.143)	(0.051)	(0.273)
$\left(P^R\right)^2$	-3.730	-2.699	0.078	-0.665
	(0.498)	(0.178)	(0.026)	(0.384)
$\left(P^R\right)^3$	1.351	1.007	2.40E-04	0.255
	(0.173)	(0.069)	(0.002)	(0.164)
W	-0.151	-0.106	0.091	0.078
	(0.171)	(0.053)	(0.107)	(0.152)
W^2	0.206	-0.005	0.389	0.511
	(0.207)	(0.064)	(0.270)	(0.276)
W^3	-0.046	0.008	-0.096	-0.306
	(0.072)	(0.022)	(0.204)	(0.144)
$P^R W$	-0.187	0.069	-0.546	-0.571
	(0.101)	(0.029)	(0.055)	(0.114)
$Load$	0.008	0.010	0.021	0.034
	(0.001)	(0.001)	(0.000)	(0.002)
$Load^2$	-8.91E-06	-4.89E-06	-2.63E-05	-1.19E-04
	(1.48E-06)	(9.93E-07)	5.18E-07	(7.86E-06)
$Load_{t-1}$	-3.53E-05	0.0851	-0.119	3.47E-04
	(0.001)	(0.029)	(0.020)	(0.002)
$Load_{t-2}$	0.001	-0.001	-1.33E-05	0.004
	(0.001)	(0.001)	(2.39E-04)	(0.002)
$Load_{t-3}$	4.49E-04	0.001	1.08E-03	0.002
	(0.001)	(0.001)	(2.56E-04)	(0.002)
$Load_{t-4}$	3.28E-04	2.26E-05	3.35E-04	0.001
	(0.001)	(0.001)	(2.56E-04)	(0.002)
$Load_{t-5}$	0.002	1.18E-04	1.42E-04	0.004
	(3.91E-04)	5.68E-04	(2.39E-04)	(0.001)
Obs	60,755	416,562	352,549	143,034
N	32	195	164	68
F-stat	169.32	49.76	339.83	165.05

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The dependent variable for all regions is a binary variable equal to one if daily CO_2 emissions is positive and zero otherwise. "Obs" gives total number of observations, "N" denotes number of cross-sectional units included, and "F-stat" gives the F-statistic of the hypothesis that the lagged load variables ($Load_{t-1}$ through $Load_{t-5}$) are jointly equal to zero. The $p-value$ for each F-stat is less that 0.001. Standard errors (SEs) are given in parentheses. SEs are clustered at the unit level. All specifications include unit-level and season-by-year fixed effects.

Table A.3: Capacity Factor Results - Two-step Method

	ERCOT	MISO	PJM	SPP
P^R	0.167	-0.018	-0.228	0.028
	(0.267)	(0.069)	(0.020)	(0.092)
$\left(P^R\right)^2$	-0.666	-0.236	0.075	-0.182
	(0.347)	(0.094)	(0.009)	(0.124)
$\left(P^R\right)^3$	0.294	0.124	-0.005	0.053
	(0.122)	(0.038)	(8.56e-04)	(0.051)
W	-0.018	-0.046	0.035	-0.017
	(0.014)	(0.007)	(0.020)	(0.021)
W^2	-0.016	0.011	-0.017	-0.011
	(0.021)	(0.011)	(0.045)	(0.033)
W^3	0.011	-0.006	-0.024	-0.005
	(0.008)	(0.004)	(0.032)	(0.016)
$P^R W$	-0.070	0.018	-0.034	-0.091
	(0.022)	(0.012)	(0.022)	(0.042)
$Load$	0.002	0.002	0.003	0.004
	(2.34e-04)	(4.20e-04)	(2.98e-04)	(5.03e-04)
$Load^2$	-2.30e-06	-3.64e-06	-2.32e-06	-1.45e-05
	(3.22e-07)	(1.51e-06)	(3.93e-07)	(1.83e-06)
λ	0.147	-0.145	-0.119	0.028
	(0.033)	(0.033)	(0.027)	(0.038)
Obs	57,575	335,227	261,929	123,077
N	32	195	168	68

'Obs" gives total number of observations and "N" denotes number of cross-sectional units included in the intensity equation. Standard errors (SEs) are given in parentheses. SEs are clustered at the unit level for all ISOs. The variable "Age" was dropped for SPP due to collinearity.

Table A.4: CO_2 Emission Results - Two-step Method

	ERCOT	MISO	PJM	SPP
P^R	-0.185	0.002	-0.224	-0.033
	(0.251)	(0.080)	(0.0232)	(0.128)
$\left(P^R\right)^2$	-0.291	-0.287	0.0761	-0.010
	(0.318)	(0.106)	(0.0115)	(0.181)
$\left(P^R\right)^3$	0.185	0.145	-0.00544	-0.065
	(0.108)	(0.041)	(0.00105)	(0.085)
W	-0.0308	-0.064	0.000312	-0.043
	(0.018)	(0.009)	(0.0221)	(0.024)
W^2	-0.015	0.013	0.0318	-0.004
	(0.027)	(0.013)	(0.0472)	(0.036)
W^3	0.011	-0.007	-0.0583	-0.008
	(0.010)	(0.004)	(0.0334)	(0.018)
$P^R W$	-0.054	0.032	-0.0163	-0.066
	(0.020)	(0.014)	(0.0223)	(0.048)
$Load$	0.002	0.003	0.00251	0.006
	(2.83e-04)	(5.05e-04)	(3.07e-04)	(5.83e-04)
$Load^2$	-2.58e-06	-4.16e-06	-2.32e-06	-1.59e-05
	(4.00e-07)	(1.80e-06)	(4.06e-07)	(2.11e-06)
λ	0.122	-0.134	-0.138	0.061
	(0.037)	(0.038)	(0.027)	(0.044)
Obs	57,574	335,213	256,741	123,065
N	32	195	164	68

'Obs" gives total number of observations and "N" denotes number of cross-sectional units included in the intensity equation. Standard errors (SEs) are given in parentheses. SEs are clustered at the unit level for all ISOs. The variable "Age" was dropped for SPP due to collinearity.

Table A.5: Two-step Method Marginal Effects

	ERCOT		MISO		PJM		SPP	
	$\partial CF/\partial P^R$	$\partial CF/\partial W$	$\partial CF/\partial P^R$	$\partial CF/\partial W$	$\partial CF/\partial P^R$	$\partial CF/\partial W$	$\partial CF/\partial P^R$	$\partial CF/\partial W$
2008	-0.102	-0.042	-0.100	-0.037	-0.183	0.022	-0.062	-0.042
	(0.133)	(0.007)	(0.037)	(0.004)	(0.017)	(0.012)	(0.044)	(0.014)
2013	-0.391	-0.062	-0.136	-0.031	-0.130	-0.018	-0.180	-0.085
	(0.054)	(0.008)	(0.020)	(0.004)	(0.017)	(0.005)	(0.029)	(0.011)

	ERCOT		MISO		PJM		SPP	
	$\partial E/\partial P^R$	$\partial E/\partial W$	$\partial E/\partial P^R$	$\partial E/\partial W$	$\partial E/\partial P^R$	$\partial E/\partial W$	$\partial E/\partial P^R$	$\partial E/\partial W$
2008	-0.303	-0.050	-0.096	-0.051	-0.178	-0.000	-0.060	-0.060
	(0.128)	(0.007)	(0.044)	(0.005)	(0.019)	(0.014)	(0.063)	(0.016)
2013	-0.410	-0.064	-0.143	-0.039	-0.119	-0.017	-0.145	-0.095
	(0.050)	(0.010)	(0.023)	(0.005)	(0.015)	(0.007)	(0.036)	(0.011)

Marginal effects are inclusive of the effect of variables on the inverse Mills ratio. "2008" rows refer to marginal effects calculated using 2008 variable averages. "2013" rows refer to marginal effects calculated using 2013 variable averages. Bootstrapped standard errors are given in parentheses below the marginal effect estimates.

Table A.6: Two-Step Method Marginal Effects - Drop if $y_{it-1} = 0$ & $y_{it} > 0$

	ERCOT		MISO		PJM		SPP	
	$\partial CF/\partial P^R$	$\partial CF/\partial W$	$\partial CF/\partial P^R$	$\partial CF/\partial W$	$\partial CF/\partial P^R$	$\partial CF/\partial W$	$\partial CF/\partial P^R$	$\partial CF/\partial W$
2008	-0.099	-0.043	-0.091	-0.038	-0.199	0.027	-0.056	-0.041
	(0.128)	(0.006)	(0.036)	(0.004)	(0.017)	(0.011)	(0.043)	(0.013)
2013	-0.398	-0.061	-0.141	-0.035	-0.151	-0.017	-0.180	-0.084
	(0.052)	(0.008)	(0.019)	(0.004)	(0.015)	(0.005)	(0.029)	(0.011)

	ERCOT		MISO		PJM		SPP	
	$\partial E/\partial P^R$	$\partial E/\partial W$	$\partial E/\partial P^R$	$\partial E/\partial W$	$\partial E/\partial P^R$	$\partial E/\partial W$	$\partial E/\partial P^R$	$\partial E/\partial W$
2008	-0.304	-0.050	-0.085	-0.052	-0.185	0.008	-0.060	-0.058
	(0.125)	(0.006)	(0.044)	(0.005)	(0.019)	(0.013)	(0.064)	(0.016)
2013	-0.417	-0.063	-0.147	-0.041	-0.130	-0.017	-0.144	-0.096
	(0.049)	(0.009)	(0.022)	(0.005)	(0.015)	(0.007)	(0.037)	(0.012)

Robustness check that drops days following a start-up. Marginal effects are inclusive of the effect of variables on the inverse Mills ratio. "2008" rows refer to marginal effects calculated using 2008 variable averages. "2013" rows refer to marginal effects calculated using 2013 variable averages. Bootstrapped standard errors are given in parentheses below the marginal effect estimates.

Table A.7: Two-Step Method Marginal Effects - Using $Load_{t-2}$ - $Load_{t-5}$

	ERCOT		MISO		PJM		SPP	
	$\partial CF/\partial P^R$	$\partial CF/\partial W$	$\partial CF/\partial P^R$	$\partial CF/\partial W$	$\partial CF/\partial P^R$	$\partial CF/\partial W$	$\partial CF/\partial P^R$	$\partial CF/\partial W$
2008	-0.102	-0.042	-0.100	-0.037	-0.189	0.022	-0.062	-0.042
	(0.133)	(0.007)	(0.037)	(0.004)	(0.016)	(0.012)	(0.044)	(0.014)
2013	-0.391	-0.062	-0.136	-0.031	-0.138	-0.018	-0.180	-0.085
	(0.054)	(0.008)	(0.020)	(0.004)	(0.015)	(0.005)	(0.029)	(0.011)

	ERCOT		MISO		PJM		SPP	
	$\partial E/\partial P^R$	$\partial E/\partial W$	$\partial E/\partial P^R$	$\partial E/\partial W$	$\partial E/\partial P^R$	$\partial E/\partial W$	$\partial E/\partial P^R$	$\partial E/\partial W$
2008	-0.303	-0.050	-0.096	-0.051	-0.178	-0.000	-0.060	-0.060
	(0.128)	(0.007)	(0.044)	(0.005)	(0.019)	(0.014)	(0.063)	(0.016)
2013	-0.410	-0.064	-0.142	-0.039	-0.119	-0.017	-0.145	-0.095
	(0.050)	(0.010)	(0.023)	(0.005)	(0.015)	(0.007)	(0.036)	(0.011)

Robustness check that only includes lagged load $Load_{t-2}$ - $Load_{t-5}$ in selection step estimation. Marginal effects are inclusive of the effect of variables on the inverse Mills ratio. "2008" rows refer to marginal effects calculated using 2008 variable averages. "2013" rows refer to marginal effects calculated using 2013 variable averages. Bootstrapped standard errors are given in parentheses below the marginal effect estimates.

B Robustness Checks

This section presents and discusses a series of alternative estimations to examine the robustness of the main results presented in the main text. The first of these robustness checks includes daily electricity demand (load) from surrounding regions outside of the ISO in question. For ERCOT, the external load variables included were those labeled SPP and the southern part of the MISO region in Figure C.2.[26]. The external loads for MISO include the regions labeled MRO-MAPP, SERC-North, WECC-NWPP, NPCC-Ontario, SPP, and PJM in Figure C.2 The external loads used for PJM are those labeled in the figure as NYISO, SERC-North, SERC-East, and the northern MISO region. Finally, for SPP we included load variables from ERCOT, WECC-RMRG, WECC-SWSG, the northern MISO region, and the southern MISO region.

The median-quantile parameter estimates with these external loads included are given in Tables B.1 and B.2. The corresponding marginal effects, based on 2008 and 2013 averages along with "counterfactual" marginal effects, are given in Table B.3. From Tables B.1 and B.2, the outside load variables are generally positive and statistically significant. However, the inclusion of these load variables do little to change the other key parameters of the model relative to our baseline specification. The marginal effects are also quite similar to those given in Tables 4 and 5.

Similarly, wind generation from surrounding areas outside of the ISO being examined may also affect the within-ISO coal units. We therefore next explored specifications that controlled for wind generation from the surrounding ISOs. More specifically, for the ERCOT

[26]Note that while the ISO MISO currently contains this southern region, our analysis of MISO excludes this region as it was not part of MISO for our entire sample. In the tables below, we label this southern region as "MISO-S" for MISO-South.

specifications we included wind generation from SPP, for MISO we included wind generation from SPP and PJM, for PJM we included with generation from MISO, and for SPP we included wind generation from ERCOT and MISO.[27] The surrounding area load was based on known interconnections and regional proximities to NERC Assessment Areas as seen in Figure C.2. The parameter estimate results with these additional controls are given in Tables B.4 and B.5. These results are again quite similar to our base specifications. The marginal effects, given in Table B.6, are also nearly the same as those from the primary results.

The next specification check alters the polynomial order of the price ratio and wind generation variables to see if our estimated marginal effects are sensitive to these alterations. We estimate a first order polynomial model (i.e., including only P^R and W as controls and no higher order variants of these terms) and a fourth order polynomial model (i.e., adding the controls $(P^R)^4$ and W^4 to our base specification). Parameter estimates from these specifications are given in Tables B.7, B.8, B.9, and B.10. The corresponding marginal effects are given in Tables B.11 and B.12. The parameter estimates for these specifications obviously deviate from our baseline specification, but we again find negative and statistically significant interaction effects across the regions, except for MISO. The marginal effects are also numerically quite similar to the results presented for the baseline specifications, demonstrating the robustness of the results. Though not shown here, we also estimated the external load, first-order, and fourth-order specifications under the two-step estimation technique. Similar to the results presented here for the quantile regression technique, we find that the

[27] California ISO (CAISO) and Bonneville Power Authority (BPA) also have significant wind generation, however these regions only have a single coal plant and thus fall outside the scope of our research question. We also analyzed data from ISO-New England (ISONE) and New York ISO (NYISO). However, due to low wind generation, few operating coal power plants, and the implementation of the Regional Greenhouse Gas Initiative (RGGI) during the time span analyzed, we opted to omit these regions.

two-step estimations of these specifications largely concur with the results presented in the main text and provide numerically similar marginal effects to those presented above.

We also consider several specifications that more fully exploit some of the hourly data that we have. The first of these specifications replaces wind generation (W_t) in equations (3) and (2) with the variable $(W/L)_t$, where $(W/L)_t$ is day t's average of the hourly wind-to-load ratio. The intent here is that $(W/L)_t$ will pick up the relative importance of wind generation across the day relative to load in ways that wind generation levels cannot. The parameter results for this specification are included in Tables B.13 and B.14, with corresponding marginal effects given in Table B.15. Again, with this specification we find statistically significant interaction effects and the marginal effects move in a similar fashion as in our base specifications.

Next, we explore responses during offpeak and peak hours. Tables B.16 and B.16 give the parameter estimates using offpeak hours. For this specification, instead of using daily CF_{it}, $Wind_t$, and $Load_{it}$ measures in equations (3) and (2), we replace these variables with these variables calculated over the offpeak hours (hours beginning 12:00 am - 7:00 am and 8:00 pm - 11:00 pm) for day t.[28] These results are again qualitatively similar to the base case results, as are the marginal effects shown in Table B.18.

Finally, we also explore responses during peak hours. The peak hours are defined as hours beginning 8:00 am - 7:00 pm and the variables CF_{it}, $Wind_t$, and $Load_{it}$ are formed over these hours for these specifications. The results of the peak hour analysis are given in Tables B.19 and B.20, with marginal effects given in B.21. Once again, the basic story remains consistent with this specification.

[28]Specifically, the offpeak CF_{it} is calculated as the net generation over the offpeak hours divided by the max generating capacity over the offpeak hours, $Wind_t$ is the sum of wind generation in the offpeak hours, and $Load_{it}$ is the sum of the load over offpeak hours in unit i's transmission zone on day t.

Table B.1: Capacity Factor Results - Median Quantile with External Loads

	ERCOT	MISO	PJM	SPP
P^R	0.358	-0.0508	-0.0626	0.0708
	(0.265)	(0.142)	(0.0696)	(0.118)
$\left(P^R\right)^2$	-0.849	-0.184	-0.0702	-0.215
	(0.347)	(0.199)	(0.0584)	(0.175)
$\left(P^R\right)^3$	0.347	0.101	0.00763	0.0621
	(0.116)	(0.0741)	(0.00505)	(0.0765)
W	-0.00193	-0.0332	0.0616	0.00486
	(0.0128)	(0.00626)	(0.0217)	(0.0202)
W^2	0.00118	0.00200	0.00948	0.00937
	(0.0140)	(0.00998)	(0.0390)	(0.0381)
W^3	0.00330	-0.00425	-0.0294	-0.00566
	(0.00445)	(0.00326)	(0.0294)	(0.0187)
$P^R W$	-0.117	0.0160	-0.121	-0.185
	(0.0381)	(0.0117)	(0.0293)	(0.0474)
$MRO - MAPP$		1.09e-06		5.68e-08
		(1.57e-07)		(1.66e-07)
$SERC - N$		5.63e-08	2.04e-08	
		(1.30e-08)	(1.88e-08)	
$SERC - E$			5.58e-08	
			(1.44e-08)	
$WECC - NWPP$		-2.79e-09		
		(1.26e-08)		
$NPCC$		1.95e-07		
		(3.46e-08)		
$MISO - S$	1.76e-07			5.64e-08
	(4.09e-08)			(2.25e-08)
$WECC - RMRG$				3.37e-07
				(7.39e-08)
$ERCOT$				1.90e-09
				(9.32e-09)
$MISO$			8.44e-08	1.03e-07
			(1.41e-08)	(1.23e-08)
$NYISO$			8.02e-08	
				5.88e-08
$WECC - SWSG$				(2.33e-08)
				(2.08e-08)
SPP	2.73e-08	9.92e-09		
	(2.14e-08)	(1.09e-08)		
PJM		1.86e-08		
		(3.49e-09)		
Obs	60,084	396,985	301,083	139,667

Standard errors are given in parentheses below the parameter estimates. Parameters associated with the external load variables are denoted by the NERC Assessment Area labels. Other controls not shown are the same as the base specifications given in the main text.

Table B.2: CO_2 Emission Results - Median Quantile with External Loads

	ERCOT	MISO	PJM	SPP
P^R	-0.0943	0.274	-0.146	-0.0391
	(0.300)	(0.127)	(0.0810)	(0.133)
$\left(P^R\right)^2$	-0.378	-0.654	-0.00927	0.0582
	(0.362)	(0.197)	(0.0642)	(0.181)
$\left(P^R\right)^3$	0.213	0.271	0.00237	-0.116
	(0.116)	(0.0885)	(0.00552)	(0.0752)
W	-0.0339	-0.0477	0.0598	-0.0202
	(0.0159)	(0.00817)	(0.0253)	(0.0249)
W^2	0.0145	0.00816	-0.00431	0.0160
	(0.0151)	(0.0136)	(0.0429)	(0.0405)
W^3	-0.00125	-0.00677	-0.0221	-0.00996
	(0.00499)	(0.00423)	(0.0322)	(0.0199)
$P^R W$	-0.0797	0.0174	-0.103	-0.159
	(0.0374)	(0.0174)	(0.0345)	(0.0617)
$MRO - MAPP$		9.28e-07		-8.13e-08
		(1.86e-07)		(2.55e-07)
$SERC - N$		6.61e-08	4.21e-08	
		(1.61e-08)	(1.98e-08)	
$SERC - E$			4.46e-08	
			(1.58e-08)	
$WECC - NWPP$		1.44e-08		
		(1.65e-08)		
$NPCC$		2.64e-07		
		(3.76e-08)		
$MISO - S$	2.24e-07			7.49e-08
	(5.49e-08)			(2.68e-08)
$WECC - RMRG$				3.47e-07
				(8.75e-08)
$ERCOT$				-3.27e-09
				(1.29e-08)
$MISO$			8.19e-08	1.21e-07
			(1.37e-08)	(1.47e-08)
$NYISO$			6.75e-08	
			(2.43e-08)	
$WECC - SWSG$				-1.10e-07
				(2.53e-08)
SPP	5.31e-08	4.24e-08		
	(3.08e-08)	(1.55e-08)		
PJM		4.24e-08		
		(1.55e-08)		
Obs	60,187	397,484	302,121	139,958

Standard errors are given in parentheses below the parameter estimates. Parameters associated with the external load variables are denoted by the NERC Assessment Area labels. Other controls not shown are the same as the base specifications given in the main text.

Table B.3: Quantile Median Marginal Effects with External Load

	Panel A. $\frac{\partial CF}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.009	-0.114	-0.110	-0.050
	(0.130)	(0.065)	(0.040)	(0.049)
2013 Actual	-0.369	-0.146	-0.203	-0.228
	(0.071)	(0.030)	(0.020)	(0.034)
2013 Counterfactual	-0.313	-0.158	-0.166	-0.129
	(0.062)	(0.027)	(0.019)	(0.021)
	Panel B. $\frac{\partial CF}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.024	-0.029	0.030	-0.046
	(0.008)	(0.004)	(0.013)	(0.010)
2013 Actual	-0.057	-0.032	-0.035	-0.084
	(0.006)	(0.004)	(0.007)	(0.010)
2013 Counterfactual	-0.017	-0.038	0.022	-0.047
	(0.011)	(0.007)	(0.012)	(0.019)
	Panel C. $\frac{\partial E}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.261	0.027	-0.160	-0.057
	(0.154)	(0.059)	(0.049)	(0.062)
2013 Actual	-0.389	-0.203	-0.198	-0.181
	(0.051)	(0.031)	(0.023)	(0.042)
2013 Counterfactual	-0.351	-0.216	-0.166	-0.096
	(0.041)	(0.034)	(0.023)	(0.028)
	Panel D. $\frac{\partial E}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.040	-0.041	0.030	-0.053
	(0.009)	(0.005)	(0.015)	(0.015)
2013 Actual	-0.055	-0.040	-0.031	-0.093
	(0.008)	(0.005)	(0.007)	(0.013)
2013 Counterfactual	-0.028	-0.047	0.017	-0.050
	(0.012)	(0.011)	(0.016)	(0.024)

"2008 Actual" and "2013 Actual" are marginal effects calculated using 2008 or 2013 variable averages. "2013 Counterfactual" in Panels A and C hold W at 2008 averages and in Panels B and D hold P^R at 2008 averages in the calculation of the marginal effects. Standard errors are given in parentheses below the estimated marginal effects.

Table B.4: Capacity Factor Results: Median Quantile with External Wind Controls

	ERCOT	MISO	PJM	SPP
P^R	0.352	0.287	-0.0978	0.0273
	(0.273)	(0.0891)	(0.0787)	(0.0737)
$\left(P^R\right)^2$	-0.851	-0.761	-0.0590	-0.138
	(0.364)	(0.133)	(0.0679)	(0.0664)
$\left(P^R\right)^3$	0.348	0.332	0.00695	0.0154
	(0.120)	(0.0589)	(0.00589)	(0.00658)
W	0.00881	-0.0371	0.0528	0.0141
	(0.0122)	(0.00672)	(0.0273)	(0.0196)
W^2	-0.0122	-0.00295	0.0842	0.0302
	(0.0153)	(0.0107)	(0.0474)	(0.0315)
W^3	0.00840	-0.00287	-0.0777	-0.0259
	(0.00520)	(0.00337)	(0.0376)	(0.0158)
$P^R W$	-0.115	0.0211	-0.155	-0.175
	(0.0364)	(0.0145)	(0.0386)	(0.0525)
W_{ERCOT}				-1.03e-08
				(1.45e-08)
W_{MISO}			-2.17e-08	-1.19e-07
			(1.52e-08)	(2.29e-08)
W_{PJM}		-8.97e-08		
		(2.97e-08)		
W_{SPP}	-6.50e-08	1.88e-09		
	(4.48e-08)	(2.25e-08)		
Obs	60,383	376,358	294,060	140,184

Standard errors are given in parentheses below the parameter estimates. Parameters associated with the external wind generation variables are denoted by the ISO labels. All external wind generation variables are in MWhs. Other controls not shown are the same as the base specifications given in the main text.

Table B.5: CO_2 Emissions Results: Median Quantile with External Wind Controls

	ERCOT	MISO	PJM	SPP
P^R	-0.0954	0.322	-0.107	0.0989
	(0.287)	(0.114)	(0.0911)	(0.0874)
$\left(P^R\right)^2$	-0.388	-0.810	-0.0527	-0.216
	(0.347)	(0.171)	(0.0761)	(0.0748)
$\left(P^R\right)^3$	0.215	0.347	0.00643	0.0229
	(0.113)	(0.0767)	(0.00658)	(0.00733)
W	-0.0168	-0.0460	0.0407	0.00411
	(0.0139)	(0.00793)	(0.0338)	(0.0229)
W^2	-0.00651	-0.00143	0.0307	-0.000906
	(0.0187)	(0.0131)	(0.0564)	(0.0404)
W^3	0.00597	-0.00333	-0.0381	-0.0118
	(0.00657)	(0.00417)	(0.0452)	(0.0203)
$P^R W$	-0.0764	0.0283	-0.110	-0.130
	(0.0358)	(0.0163)	(0.0447)	(0.0594)
W_{ERCOT}				-9.08e-09
				(2.06e-08)
W_{MISO}			-8.29e-09	-1.44e-07
			(1.51e-08)	(2.81e-08)
W_{PJM}		-1.61e-07		
		(3.64e-08)		
W_{SPP}	-3.59e-08	-2.36e-08		
	(5.35e-08)	(2.62e-08)		
Obs	60,363	379,871	292,247	140,328

Standard errors are given in parentheses below the parameter estimates. Parameters associated with the external wind generation variables are denoted by the ISO labels. All external wind generation variables are given in MWhs. Other controls not shown are the same as the base specifications given in the main text.

Table B.6: Quantile Median Marginal Effects with External Wind Controls

	Panel A. $\frac{\partial CF}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.015	0.019	-0.143	-0.063
	(0.131)	(0.044)	(0.045)	(0.040)
2013 Actual	-0.375	-0.230	-0.237	-0.223
	(0.075)	(0.025)	(0.024)	(0.032)
2013 Counterfactual	-0.320	-0.246	-0.189	-0.129
	(0.067)	(0.024)	(0.024)	(0.020)
	Panel B. $\frac{\partial CF}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.022	-0.034	0.024	-0.020
	(0.008)	(0.004)	(0.016)	(0.011)
2013 Actual	-0.057	-0.040	-0.034	-0.071
	(0.007)	(0.004)	(0.008)	(0.011)
2013 Counterfactual	-0.018	-0.048	0.041	-0.023
	(0.012)	(0.008)	(0.017)	(0.019)
	Panel C. $\frac{\partial E}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.265 7	0.037	-0.144	-0.020
	(0.146)	(0.057)	(0.053)	(0.053)
2013 Actual	-0.397	-0.230	-0.219	-0.194
	(0.049)	(0.029)	(0.025)	(0.039)
2013 Counterfactual	-0.360	-0.251	-0.185	-0.124
	(0.040)	(0.030)	(0.025)	(0.028)
	Panel D. $\frac{\partial E}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.036	-0.041	0.016	-0.028
	(0.008)	(0.005)	(0.019)	(0.014)
2013 Actual	-0.057	-0.043	-0.036	-0.081
	(0.009)	(0.004)	(0.008)	(0.012)
2013 Counterfactual	-0.031	-0.054	0.017	-0.045
	(0.012)	(0.009)	(0.019)	(0.022)

"2008 Actual" and "2013 Actual" are marginal effects calculated using 2008 or 2013 variable averages. "2013 Counterfactual" in Panels A and C hold W at 2008 averages and in Panels B and D hold P^R at 2008 averages in the calculation of the marginal effects. Standard errors are given in parentheses below the estimated marginal effects.

Table B.7: Capacity Factor Results - Median Quantile with 1^{st} Order Polynomials

	ERCOT	MISO	PJM	SPP
P^R	-0.252	-0.217	-0.175	-0.106
	(0.0601)	(0.0230)	(0.0206)	(0.0207)
W	0.00668	-0.0314	0.0807	0.0161
	(0.0173)	(0.00998)	(0.0247)	(0.0280)
P^RW	-0.117	-0.0112	-0.165	-0.193
	(0.0358)	(0.0150)	(0.0363)	(0.0545)
Obs	60,377	375,725	291,717	139,955

Standard errors are given in parentheses below the parameter estimates. "Obs" gives the total number of observations used in the quantile regression. Other controls not shown are the same as the base specifications given in the main text.

Table B.8: CO_2 Emission Results - Median Quantile with 1^{st} Order Polynomials

	ERCOT	MISO	PJM	SPP
P^R	-0.311	-0.230	-0.161	-0.114
	(0.0414)	(0.0274)	(0.0225)	(0.0302)
W	-0.0109	-0.0430	0.0559	-0.00838
	(0.0179)	(0.0114)	(0.0262)	(0.0352)
P^RW	-0.0857	6.90e-05	-0.125	-0.158
	(0.0356)	(0.0170)	(0.0383)	(0.0684)
Obs	60,549	379,024	297,332	140,407

Standard errors are given in parentheses below the parameter estimates. "Obs" gives the total number of observations used in the quantile regression. Other controls not shown are the same as the base specifications given in the main text.

Table B.9: Capacity Factor Results - Median Quantile with 4^{th} Order Polynomials

	ERCOT	MISO	PJM	SPP
P^R	0.437	0.419	0.171	0.0633
	(0.462)	(0.158)	(0.109)	(0.170)
$\left(P^R\right)^2$	-1.048	-1.083	-0.463	-0.204
	(1.233)	(0.370)	(0.144)	(0.416)
$\left(P^R\right)^3$	0.523	0.654	0.189	0.0326
	(1.251)	(0.366)	(0.0580)	(0.443)
$\left(P^R\right)^4$	-0.0469	-0.110	-0.0142	0.0109
	(0.367)	(0.130)	(0.00440)	(0.160)
W	0.0449	-0.0720	-0.0212	-0.0167
	(0.0186)	(0.0104)	(0.0334)	(0.0230)
W^2	-0.0898	0.0714	0.257	0.0758
	(0.0492)	(0.0181)	(0.128)	(0.0814)
W^3	0.0728	-0.0668	-0.426	-0.0888
	(0.0388)	(0.0154)	(0.221)	(0.0951)
W^4	-0.0174	0.0174	0.202	0.0289
	(0.0103)	(0.00430)	(0.123)	(0.0358)
$P^R W$	-0.122	0.0265	-0.0762	-0.161
	(0.0349)	(0.0141)	(0.0345)	(0.0512)
Obs	60,377	375,725	291,717	139,955

Standard errors are given in parentheses below the parameter estimates. "Obs" gives the total number of observations used in the quantile regression. Other controls not shown are the same as the base specifications given in the main text.

Table B.10: CO_2 Emission Results - Median Quantile with 4^{th} Order Polynomials

	ERCOT	MISO	PJM	SPP
P^R	-0.278	0.485	0.143	0.0580
	(0.501)	(0.129)	(0.103)	(0.237)
$\left(P^R\right)^2$	0.0651	-1.209	-0.406	-0.248
	(1.297)	(0.232)	(0.125)	(0.565)
$\left(P^R\right)^3$	-0.198	0.743	0.164	0.194
	(1.265)	(0.156)	(0.0442)	(0.579)
$\left(P^R\right)^4$	0.114	-0.132	-0.0123	-0.109
	(0.365)	(0.0320)	(0.00321)	(0.200)
W	0.0265	-0.0819	-0.0201	-0.0265
	(0.0232)	(0.0127)	(0.0363)	(0.0303)
W^2	-0.103	0.0699	0.200	0.0322
	(0.0639)	(0.0236)	(0.118)	(0.118)
W^3	0.0866	-0.0660	-0.359	-0.0409
	(0.0513)	(0.0186)	(0.196)	(0.134)
W^4	-0.0215	0.0172	0.180	0.0114
	(0.0140)	(0.00513)	(0.107)	(0.0510)
$P^R W$	-0.0826	0.0367	-0.0517	-0.125
	(0.0396)	(0.0158)	(0.0364)	(0.0617)
Obs	60,146	379,438	294,574	140,075

Standard errors are given in parentheses below the parameter estimates. "Obs" gives the total number of observations used in the quantile regression. Other controls not shown are the same as the base specifications given in the main text.

Table B.11: Quantile Median Marginal Effects with 1^{st} Order Polynomials

	ERCOT	MISO	PJM	SPP
Panel A. $\frac{\partial CF}{\partial P^R}$				
2008 Actual	-0.358	-0.228	-0.241	-0.241
	(0.067)	(0.025)	(0.022)	(0.035)
2013 Actual	-0.301	-0.220	-0.190	-0.138
	(0.061)	(0.023)	(0.020)	(0.019)
Panel B. $\frac{\partial CF}{\partial W}$				
2008 Actual	-0.059	-0.038	-0.044	-0.082
	(0.007)	(0.003)	(0.007)	(0.008)
2013 Actual	-0.019	-0.034	0.036	-0.030
	(0.010)	(0.007)	(0.015)	(0.016)
Panel C. $\frac{\partial E}{\partial P^R}$				
2008 Actual	-0.388	-0.230	-0.211	-0.224
	(0.053)	(0.029)	(0.023)	(0.045)
2013 Actual	-0.347	-0.230	-0.173	-0.139
	(0.045)	(0.027)	(0.022)	(0.028)
Panel D. $\frac{\partial E}{\partial W}$				
2008 Actual	-0.059	-0.043	-0.039	-0.089
	(0.007)	(0.003)	(0.007)	(0.009)
2013 Actual	-0.029	-0.043	0.022	-0.046
	(0.011)	(0.008)	(0.016)	(0.020)

"2008 Actual" refers to marginal effects calculated at 2008 variable averages. "2013 Actual" refers to marginal effects calculated at 2013 variable averages. Standard errors are given in parentheses below the calculated marginal effects.

Table B.12: Quantile Median Marginal Effects with 4^{th} Order Polynomials

	Panel A. $\frac{\partial CF}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	0.005	0.043	-0.048	-0.053
	(0.125)	(0.050)	(0.046)	(0.049)
2013 Actual	-0.385	-0.243	-0.260	-0.226
	(0.065)	(0.026)	(0.026)	(0.032)
2013 Counterfactual	-0.326	-0.262	-0.237	-0.140
	(0.060)	(0.025)	(0.027)	(0.022)
	Panel B. $\frac{\partial CF}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.023	-0.043	-0.005	-0.037
	(0.008)	(0.004)	(0.015)	(0.011)
2013 Actual	-0.058	-0.043	-0.026	-0.084
	(0.007)	(0.005)	(0.007)	(0.012)
2013 Counterfactual	-0.017	-0.053	0.011	-0.039
	(0.012)	(0.009)	(0.016)	(0.021)
	Panel C. $\frac{\partial E}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.308	0.067	-0.048	-0.052
	(0.144)	(0.055)	(0.047)	(0.069)
2013 Actual	-0.386	-0.243	-0.232	-0.188
	(0.056)	(0.030)	(0.025)	(0.042)
2013 Counterfactual	-0.346	-0.270	-0.216	-0.121
	(0.057)	(0.031)	(0.026)	(0.031)
	Panel D. $\frac{\partial E}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.039	-0.051	-0.006	-0.049
	(0.009)	(0.005)	(0.017)	(0.014)
2013 Actual	-0.058	-0.048	-0.026	-0.090
	(0.009)	(0.005)	(0.007)	(0.011)
2013 Counterfactual	-0.030	-0.062	-0.001	-0.055
	(0.013)	(0.010)	(0.017)	(0.022)

"2008 Actual" and "2013 Actual" are marginal effects calculated using 2008 or 2013 variable averages. "2013 Counterfactual" in Panels A and C hold W at 2008 averages and in Panels B and D hold P^R at 2008 averages in the calculation of the marginal effects. Standard errors are given in parentheses below the estimated marginal effects.

Table B.13: Capacity Factor Results: Median Quantile using Wind/Load

	ERCOT	MISO	PJM	SPP
P^R	0.390	0.298	-0.0885	0.0341
	(0.249)	(0.0884)	(0.0762)	(0.0661)
$\left(P^R\right)^2$	-0.893	-0.771	-0.0570	-0.134
	(0.333)	(0.134)	(0.0643)	(0.0580)
$\left(P^R\right)^3$	0.369	0.336	0.00680	0.0154
	(0.111)	(0.0599)	(0.00556)	(0.00580)
W/L	0.00209	-0.00846	0.0111	0.000670
	(0.00122)	(0.000949)	(0.00612)	(0.00121)
$(W/L)^2$	-0.000120	0.000298	0.00596	9.62e-05
	(8.77e-05)	(0.000215)	(0.00200)	(0.000125)
$(W/L)^3$	2.85e-06	-2.47e-05	-0.00113	-6.30e-06
	(2.74e-06)	(8.61e-06)	(0.000341)	(5.00e-06)
$P^R\,(W/L)$	-0.0114	0.00265	-0.0411	-0.0116
	(0.00315)	(0.00227)	(0.00835)	(0.00277)
Obs	60,515	377,355	295,060	140,527

Standard errors are given in parentheses below the parameter estimates. The variable W/L es the average hourly wind generation divided by hourly load for a given day."Obs" gives the total number of observations used in the quantile regression. Other controls not shown are the same as the base specifications given in the main text.

Table B.14: CO_2 Emission Results: Median Quantile using Wind/Load

	ERCOT	MISO	PJM	SPP
P^R	-0.0702	0.333	-0.0855	0.101
	(0.437)	(0.108)	(0.0834)	(0.0982)
$\left(P^R\right)^2$	-0.385	-0.816	-0.0515	-0.202
	(0.890)	(0.161)	(0.0713)	(0.0886)
$\left(P^R\right)^3$	0.207	0.348	0.00624	0.0219
	(0.562)	(0.0714)	(0.00618)	(0.00875)
W/L	0.000609	-0.00968	0.00711	-0.000326
	(0.00187)	(0.00125)	(0.00658)	(0.00140)
$(W/L)^2$	-0.000124	0.000200	0.00521	7.26e-05
	(0.000145)	(0.000264)	(0.00203)	(0.000108)
$(W/L)^3$	3.31e-06	-1.93e-05	-0.00105	-5.86e-06
	(4.80e-06)	(1.07e-05)	(0.000328)	(3.65e-06)
$P^R\,(W/L)$	-0.00879	0.00419	-0.0315	-0.00946
	(0.00418)	(0.00279)	(0.00914)	(0.00338)
Obs	60,146	379,438	294,574	140,075

Standard errors are given in parentheses below the parameter estimates. The variable W/L is the average hourly wind generation divided by hourly load for a given day. "Obs" gives the total number of observations used in the quantile regression. Other controls not shown are the same as the base specifications given in the main text.

Table B.15: Quantile Median Marginal Effects with Wind/Load

	Panel A. $\frac{\partial CF}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.005	0.026	-0.139	-0.071
	(0.120)	(0.044)	(0.044)	(0.036)
2013 Actual	-0.382	-0.228	-0.243	-0.225
	(0.070)	(0.025)	(0.023)	(0.030)
2013 Counterfactual	-0.321	-0.242	-0.183	-0.135
	(0.062)	(0.024)	(0.022)	(0.020)
	Panel B. $\frac{\partial CF}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.001	-0.007	0.005	-0.002
	(0.001)	(0.001)	(0.003)	(0.001)
2013 Actual	-0.006	-0.007	-0.010	-0.006
	(0.001)	(0.001)	(0.002)	(0.001)
2013 Counterfactual	-0.002	-0.008	0.010	-0.002
	(0.001)	(0.001)	(0.003)	(0.001)
	Panel C. $\frac{\partial E}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.254	0.044	-0.128	-0.027
	(0.158)	(0.055)	(0.048)	(0.056)
2013 Actual	-0.401	-0.224	-0.214	-0.198
	(0.062)	(0.030)	(0.023)	(0.037)
2013 Counterfactual	-0.353	-0.247	-0.168	-0.124
	(0.065)	(0.029)	(0.025)	(0.028)
	Panel D. $\frac{\partial E}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.002	-0.008	0.003	-0.002
	(0.001)	(0.001)	(0.004)	(0.001)
2013 Actual	-0.006	-0.008	-0.008	-0.006
	(0.001)	(0.001)	(0.002)	(0.001)
2013 Counterfactual	-0.003	-0.010	0.007	-0.003
	(0.001)	(0.002)	(0.004)	(0.001)

"2008 Actual" and "2013 Actual" are marginal effects calculated using 2008 or 2013 variable averages. "2013 Counterfactual" in Panels A and C hold W/L at 2008 averages and in Panels B and D hold P^R at 2008 averages in the calculation of the marginal effects. Standard errors are given in parentheses below the estimated marginal effects.

Table B.16: Capacity Factor Results: Median Quantile over Off-Peak Hours

	ERCOT	MISO	PJM	SPP
P^R	0.341	0.280	0.0315	0.0778
	(0.261)	(0.0951)	(0.0988)	(0.122)
$\left(P^R\right)^2$	-0.853	-0.761	-0.217	-0.236
	(0.342)	(0.145)	(0.107)	(0.195)
$\left(P^R\right)^3$	0.349	0.334	0.0633	0.0673
	(0.114)	(0.0655)	(0.0240)	(0.0973)
W	0.0263	-0.0786	0.136	-0.0470
	(0.0300)	(0.0130)	(0.0568)	(0.0420)
W^2	-0.106	-0.0137	0.250	0.259
	(0.0584)	(0.0211)	(0.111)	(0.143)
W^3	0.0832	0.0167	-0.318	-0.341
	(0.0391)	(0.00865)	(0.101)	(0.135)
$P^R W$	-0.177	0.0187	-0.400	-0.299
	(0.0789)	(0.0287)	(0.0950)	(0.108)
Obs	60,234	375,989	262,448	140,067

Standard errors are given in parentheses below the parameter estimates. The "offpeak" hours used here are those beginning with 12:00 am - 7:00 am and 8:00 pm - 11:00 pm. "Obs" gives the total number of observations used in the quantile regression. Other controls not shown are the same as the base specifications given in the main text.

Table B.17: CO_2 Emissions Results: Median Quantile over Off-Peak Hours

	ERCOT	MISO	PJM	SPP
P^R	-0.110	0.300	-0.0313	-0.0522
	(0.274)	(0.117)	(0.0896)	(0.129)
$\left(P^R\right)^2$	-0.371	-0.793	-0.143	0.0545
	(0.321)	(0.180)	(0.0892)	(0.167)
$\left(P^R\right)^3$	0.199	0.341	0.0434	-0.120
	(0.102)	(0.0830)	(0.0180)	(0.0675)
W	-0.0152	-0.0966	0.124	-0.0910
	(0.0286)	(0.0174)	(0.0558)	(0.0532)
W^2	-0.114	-0.0211	0.168	0.259
	(0.0757)	(0.0209)	(0.1000)	(0.158)
W^3	0.0887	0.0208	-0.227	-0.354
	(0.0477)	(0.00815)	(0.0808)	(0.152)
$P^R W$	-0.0981	0.0384	-0.340	-0.227
	(0.0638)	(0.0319)	(0.0883)	(0.127)
Obs	60,217	379,350	265,118	140,231

Standard errors are given in parentheses below the parameter estimates. The "offpeak" hours used here are those beginning with 12:00 am - 7:00 am and 8:00 pm - 11:00 pm. "Obs" gives the total number of observations used in the quantile regression. Other controls not shown are the same as the base specifications given in the main text.

Table B.18: Quantile Median Marginal Effects over Off-Peak Hours

	Panel A. $\frac{\partial CF}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.021	0.010	-0.093	-0.049
	(0.125)	(0.046)	(0.048)	(0.048)
2013 Actual	-0.373	-0.243	-0.275	-0.227
	(0.071)	(0.024)	(0.027)	(0.036)
2013 Counterfactual	-0.326	-0.253	-0.205	-0.137
	(0.063)	(0.024)	(0.028)	(0.024)
	Panel B. $\frac{\partial CF}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.048	-0.077	0.049	-0.079
	(0.018)	(0.009)	(0.034)	(0.024)
2013 Actual	-0.116	-0.056	-0.093	-0.153
	(0.013)	(0.005)	(0.018)	(0.023)
2013 Counterfactual	-0.056	-0.064	0.091	-0.071
	(0.026)	(0.013)	(0.038)	(0.041)
	Panel C. $\frac{\partial E}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.266	0.019	-0.117	-0.067
	(0.143)	(0.058)	(0.046)	(0.061)
2013 Actual	-0.387	-0.241	-0.248	-0.179
	(0.045)	(0.030)	(0.027)	(0.043)
2013 Counterfactual	-0.361	-0.261	-0.189	-0.110
	(0.039)	(0.030)	(0.025)	(0.028)
	Panel D. $\frac{\partial E}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.075	-0.092	0.047	-0.107
	(0.017)	(0.012)	(0.034)	(0.031)
2013 Actual	-0.117	-0.065	-0.083	-0.167
	(0.017)	(0.005)	(0.017)	(0.022)
2013 Counterfactual	-0.083	-0.080	0.073	-0.105
	(0.027)	(0.014)	(0.036)	(0.044)

"2008 Actual" and "2013 Actual" are marginal effects calculated using 2008 or 2013 variable averages. "2013 Counterfactual" in Panels A and C hold W at 2008 averages and in Panels B and D hold P^R at 2008 averages in the calculation of the marginal effects. Standard errors are given in parentheses below the estimated marginal effects.

Table B.19: Capacity Factor Results: Median Quantile over Peak Hours

	ERCOT	MISO	PJM	SPP
P^R	0.356	0.250	0.00560	0.0789
	(0.265)	(0.0889)	(0.0879)	(0.116)
$\left(P^R\right)^2$	-0.871	-0.717	-0.200	-0.257
	(0.360)	(0.133)	(0.0941)	(0.174)
$\left(P^R\right)^3$	0.351	0.315	0.0581	0.0713
	(0.119)	(0.0588)	(0.0214)	(0.0763)
W	0.00372	-0.0696	0.120	-0.0103
	(0.0272)	(0.0118)	(0.0473)	(0.0330)
W^2	0.0349	-0.0292	-0.00382	0.107
	(0.0415)	(0.0150)	(0.155)	(0.108)
W^3	0.00397	0.0210	-0.0976	-0.162
	(0.0308)	(0.00623)	(0.236)	(0.129)
$P^R W$	-0.231	0.0272	-0.248	-0.286
	(0.0664)	(0.0223)	(0.0718)	(0.0858)
Obs	60,474	376,257	263,261	140,256

Standard errors are given in parentheses below the parameter estimates. The "peak" hours used here are those beginning with 8:00 am - 8:00 pm. "Obs" gives the total number of observations used in the quantile regression. Other controls not shown are the same as the base specifications given in the main text.

Table B.20: CO_2 Emissions Results: Median Quantile over Peak Hours

	ERCOT	MISO	PJM	SPP
P^R	-0.111	0.280	-0.0462	-0.0647
	(0.401)	(0.0947)	(0.109)	(0.132)
$\left(P^R\right)^2$	-0.355	-0.760	-0.147	0.0651
	(0.763)	(0.131)	(0.121)	(0.184)
$\left(P^R\right)^3$	0.194	0.327	0.0447	-0.130
	(0.467)	(0.0532)	(0.0306)	(0.0787)
W	-0.0459	-0.0911	0.0696	-0.0550
	(0.0265)	(0.0140)	(0.0487)	(0.0427)
W^2	0.0768	-0.0268	0.0163	0.138
	(0.0498)	(0.0155)	(0.130)	(0.119)
W^3	-0.0244	0.0213	-0.142	-0.199
	(0.0369)	(0.00611)	(0.172)	(0.127)
$P^R W$	-0.173	0.0437	-0.173	-0.227
	(0.0642)	(0.0245)	(0.0750)	(0.102)
Obs	60,458	379,693	265,769	140,389

Standard errors are given in parentheses below the parameter estimates. The "peak" hours used here are those beginning with 8:00 am - 8:00 pm. "Obs" gives the total number of observations used in the quantile regression. Other controls not shown are the same as the base specifications given in the main text.

Table B.21: Quantile Median Marginal Effects over Peak Hours

	Panel A. $\frac{\partial CF}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.012	-0.004	-0.102	-0.051
	(0.127)	(0.044)	(0.043)	(0.047)
2013 Actual	-0.378	-0.238	-0.244	-0.215
	(0.075)	(0.024)	(0.023)	(0.031)
2013 Counterfactual	-0.328	-0.251	-0.205	-0.148
	(0.066)	(0.022)	(0.023)	(0.022)
	Panel B. $\frac{\partial CF}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.033	-0.069	0.051	-0.065
	(0.013)	(0.009)	(0.027)	(0.021)
2013 Actual	-0.095	-0.054	-0.075	-0.136
	(0.014)	(0.004)	(0.016)	(0.017)
2013 Counterfactual	-0.017	-0.064	0.039	-0.058
	(0.016)	(0.010)	(0.030)	(0.033)
	Panel C. $\frac{\partial E}{\partial P^R}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.268	0.011	-0.124	-0.072
	(0.155)	(0.052)	(0.052)	(0.061)
2013 Actual	-0.394	-0.237	-0.224	-0.169
	(0.064)	(0.029)	(0.025)	(0.038)
2013 Counterfactual	-0.356	-0.258	-0.197	-0.116
	(0.060)	(0.028)	(0.027)	(0.030)
	Panel D. $\frac{\partial E}{\partial W}$			
	ERCOT	MISO	PJM	SPP
2008 Actual	-0.058	-0.086	0.023	-0.092
	(0.014)	(0.010)	(0.029)	(0.027)
2013 Actual	-0.093	-0.062	-0.068	-0.142
	(0.015)	(0.004)	(0.014)	(0.020)
2013 Counterfactual	-0.034	-0.079	0.012	-0.080
	(0.017)	(0.012)	(0.032)	(0.039)

"2008 Actual" and "2013 Actual" are marginal effects calculated using 2008 or 2013 variable averages. "2013 Counterfactual" in Panels A and C hold W at 2008 averages and in Panels B and D hold P^R at 2008 averages in the calculation of the marginal effects. Standard errors are given in parentheses below the estimated marginal effects.

C Additional Figures

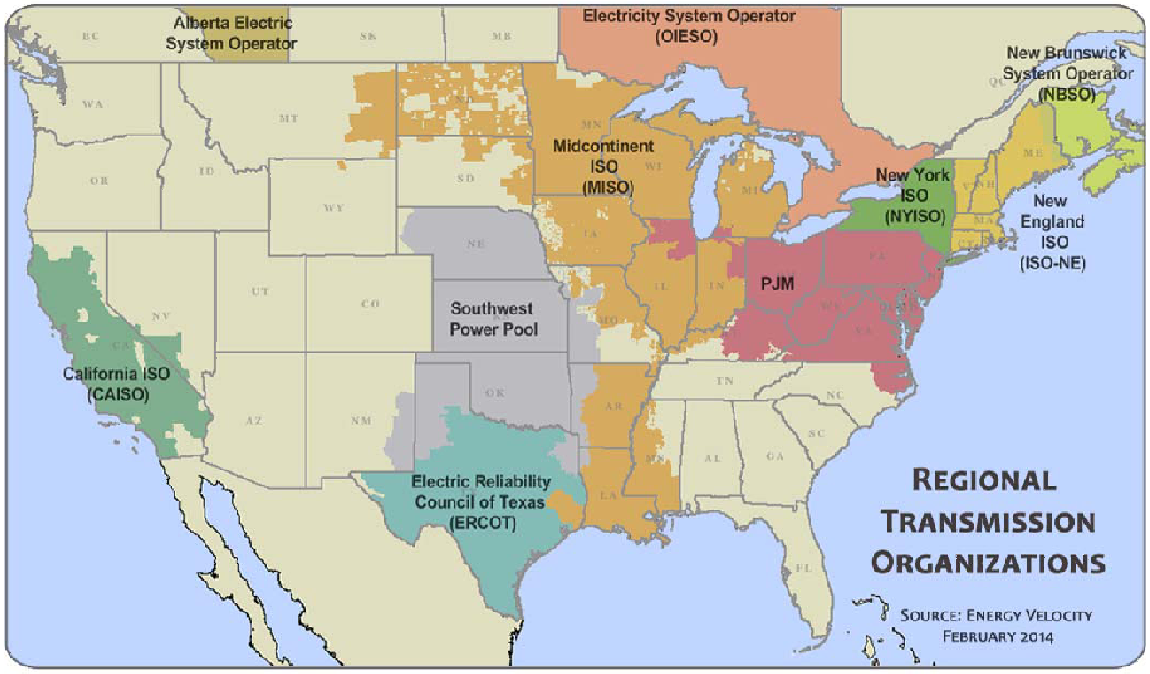

Figure C.1: United States ISO/RTO regions. ERCOT, MISO, PJM, and SPP are considered in this study. Source: Federal Energy Regulatory Commission (FERC)

Figure C.2: NERC Assessment Areas

This figure was published in the North American Electric Reliability Corporation's 2014 Summer Reliability Assessment.

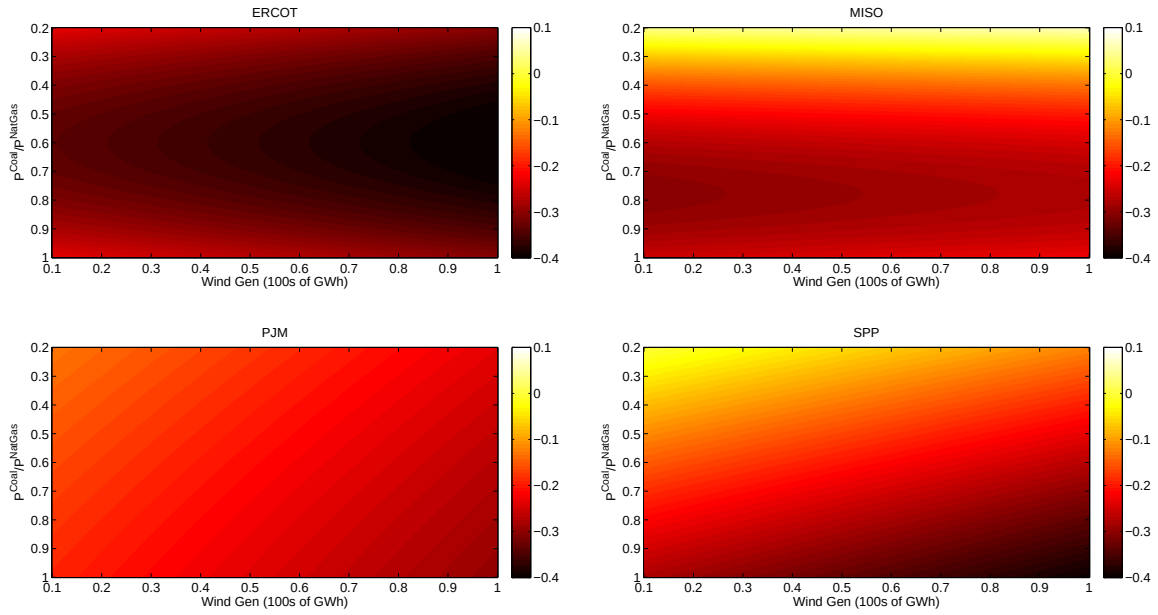

Figure C.3: Median Quantile Marginal Effects - $\frac{\partial E}{\partial P^R}$

This figure plots a range of the marginal effects of CO_2 emissions with respect to P^R based on parameter estimates given in Table 3.

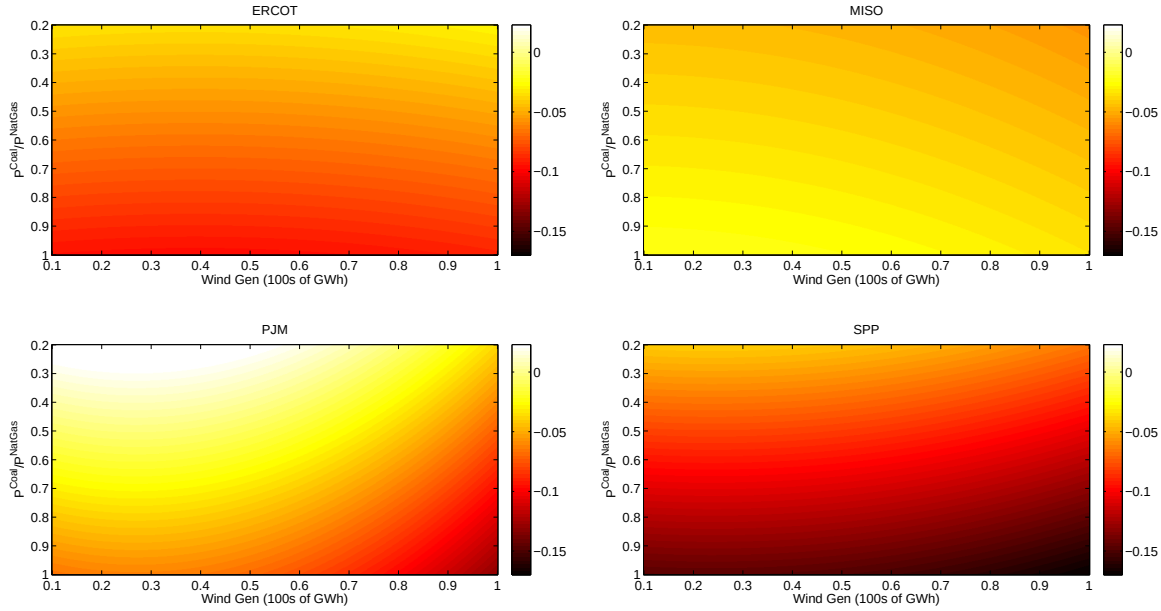

Figure C.4: Median Quantile Marginal Effects - $\frac{\partial E}{\partial W}$

This figure plots a range of the marginal effects of CO_2 emissions with respect to W based on parameter estimates given in Table 3.

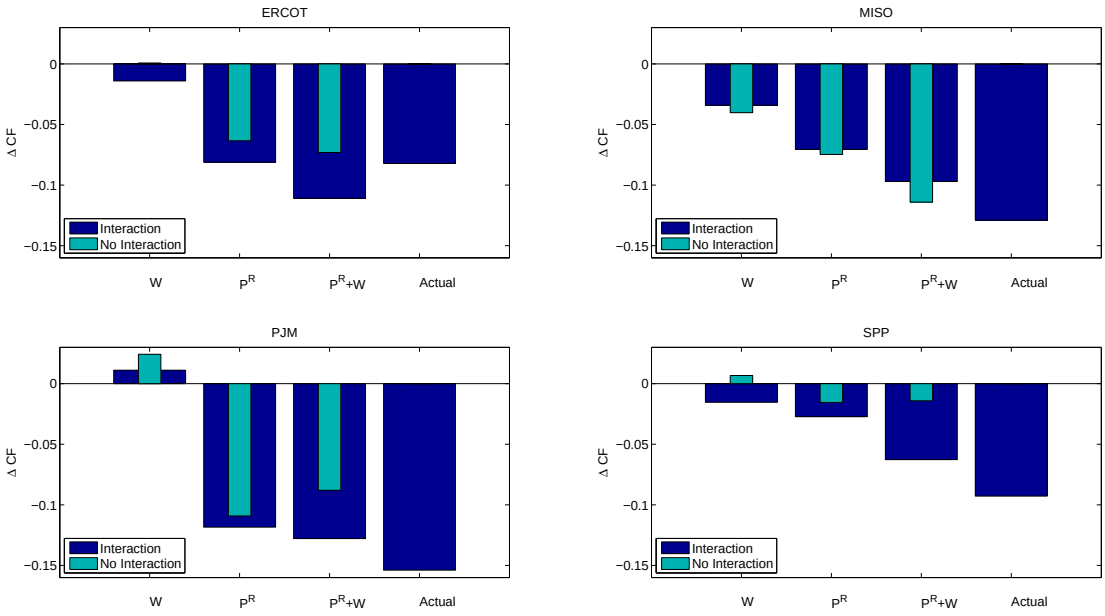

Figure C.5: Capacity Factor Change Decomposition

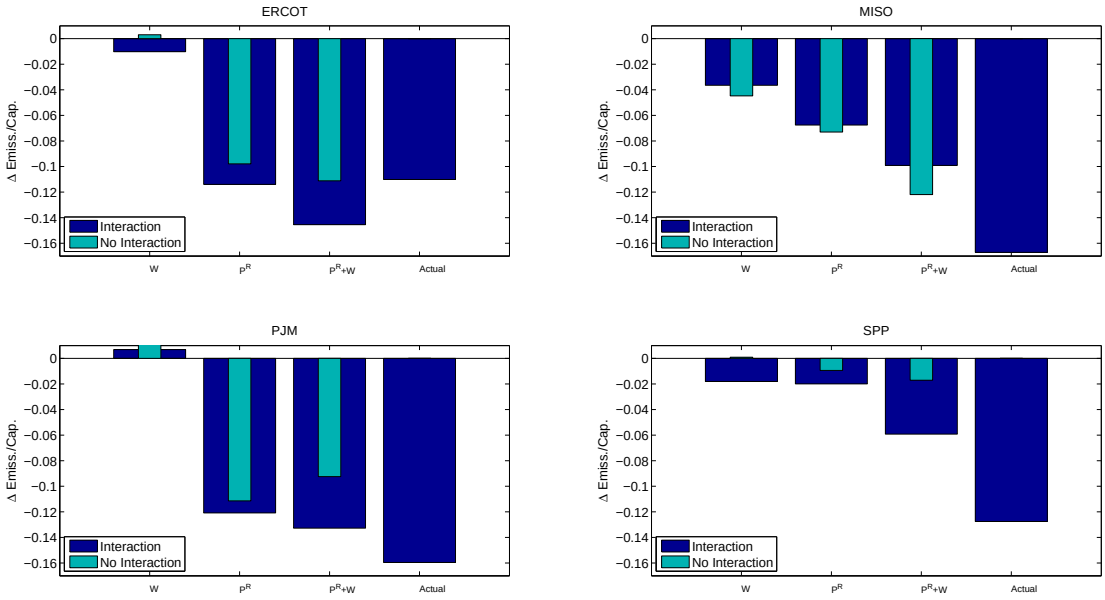

Figure C.6: Emissions Change Decomposition