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Emissions savings from wind power generation: Evidence from Texas, California and the Upper Midwest*

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ABSTRACT

Wind power has the potential to reduce emissions associated with conventional electricity generation. Using detailed, systemic hourly data of wind generation and emissions from plants in ERCOT (Texas), CAISO (California), and MISO (Upper Midwest), we estimate the SO_2, NO_x and CO_2 emissions offset by wind generation in those territories. Our estimation strategy implicitly captures both the marginal unit of generation displaced by wind on the electrical grid, and the marginal emissions reduction from that displaced unit. Our results reveal substantial variation in emissions reduction by territory, which appear to be strongly driven by differences in the existing generation mix. While the environmental benefits from emissions reductions in the Upper Midwest roughly cover government subsidies for wind generation, environmental benefits in Texas and California fall short.

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1 Introduction

Production of electricity from wind energy has risen rapidly in the last decade, with installed capacity doubling every three years in the United States (World Wind Energy Association 2009) and wind generation accounting for 2% of world consumption. As of 2010, China, the United States, and Germany were the world leaders in installed wind power generation capacity, with 44 gigawatts (GW), 40 GW and 27 GW of capacity respectively, with over 50 GW of capacity installed across the European Union. Technological advances in wind turbine design, control and siting have led to falling costs per megawatt-hour (MWh) and increased the penetration of wind energy into the power sector. In addition, government subsidies and policies have also played an important role in encouraging wind power production. For example, in the United States a majority of states have implemented Renewable Portfolio Standards mandating that a percentage of total state electricity generation be derived from renewable sources, and the federal government provides a Production Tax Credit of $22 dollars per MWh to wind power producers.

Government support for wind power development is frequently predicated on the environmental benefits of avoided emissions, such as sulphur dioxide (SO_2), nitrogen oxides (NO_x), and carbon dioxide (CO_2). It is these avoided emissions that form the focus of our study.[1] In particular we ask, what is the emissions savings rate for SO_2, NO_x and CO_2 per MWh

[1] Clearly there are other considerations beyond emission savings that can influence the nature and degree of government intervention in energy markets. For example, negative externalities from upstream production activities or reliability costs associated with accommodating wind's volatility on the grid (Bonneville Power Authority (BPA) has introduced a 0.6 cents/MWh wind integration charge). Policies that encourage wind development such as Renewable Portfolio Standards are also often portrayed as economic stimulus and green job creators (Fischlein et al. 2010).

of wind power produced, and how does that savings rate vary across regions with different existing generation mixes? To answer these questions, we consider more than 50,000 hourly observations of wind generation and emissions from power plants in the territories of the Electric Reliability Council of Texas (ERCOT), California Independent System Operator (CAISO) and the Midwest Independent System Operator (MISO).

Electricity generation in the United States relies heavily on fossil fuel sources. As of 2011, coal accounts for 42% of total generation while natural gas accounts for 25% of total generation, compared to 19% for nuclear, 8% for hydropower, 3% for wind power, and less than 1% each for solar, geothermal and biomass.[2] Average emission rates in the United states for coal-based generation are 13 lbs/MWh of SO_2, 6.0 lbs/MWh of NO_x, and 1.1 tons/MWh of CO_2; average emission rates for natural gas-based generation are substantially below those of coal, at 0.10 lbs/MWh of SO_2, 1.7 lbs/MWh of NO_x, and 0.57 tons/MWh of CO_2.[3] If a MWh of wind replaced a MWh proportional to the US generation mix, emissions of 5.5 lbs of SO_2, 2.9 lbs of NO_x and 0.61 tons of CO_2 would be avoided under average emission rates.

However, there is reason to believe that calculating the emissions savings from wind by replacing an average unit of generation and using average emission rates is an incorrect methodology. Several studies have noted that wind energy requires backup generation, such as gas, to account for the intermittency of stochastic wind power generation (Been-

[2] From Energy Information Administration (EIA) http://www.eia.gov/electricity/monthly/index.cfm. Percentages do not sum to 100% due to independent rounding.

[3] From U.S. EPA, eGRID 2000 (http://www.epa.gov/cleanenergy/energy-and-you/affect/air-emissions.html). It should be noted that average emission rates can vary substantially by region and by plant.

stock 1995; Puga 2010) even at low levels of wind penetration (Decarolis and Keith 2006).[4] Other studies have considered the use of hydropower (Benitez et al. 2008) or compressed air storage (Decarolis and Keith 2006; Denholm et al. 2005; Sioshansi 2011) as non-fossil backup generation when wind power production declines. Back-of-the-envelope calculations by Lang (2009) incorporating emissions from natural gas backup generation suggest that CO_2 emissions savings may be very small (less than 0.1 tons/MWh).

In addition to concerns about backup generation, other studies have stressed the fact that rather than displacing a representative unit of power generation, wind is likely to displace generation from higher marginal cost sources that can easily accommodate wind power on the grid - most likely natural gas. Moore et al. (2010) stress the importance of the emissions profile of the marginal power plant in terms of measuring emissions savings, while Campbell (2009) presents a theoretical exercise and notes that emissions may increase if wind intermittency leads to increases in carbon-intensive accommodating sources. In an econometric study, Cullen (2011) uses plant-level generation data from ERCOT 2005-2007 to estimate the marginal change in generation at each plant per MWh of wind generated in ERCOT. He finds that for every 1 MWh of wind power generated, 0.72 MWh of gas and 0.28 MWh of coal are displaced.[5] Applying average plant emission rates to the marginal change in generation by plant, Cullen calculates that 3.15 lbs of SO_2, 1.05 lbs of NO_x, and 0.71 tons of CO_2 were avoided per MWh of wind power.

Yet, average plant emission rates may not appropriately reflect the actual emissions

[4] The stochastic nature of wind itself is exacerbated by the fact that wind power generation is proportional to the *cube* of wind speed. Thus a doubling/halving of wind speed leads to an eightfold increase/decrease in generation.

[5] By contrast, the mix of generation in ERCOT is 47% gas and 38% coal during the 2005-2007 time period.

savings from wind generation. Liik et al. (2003) raise the concern that rapid ramping of fossil fuel plants (known as cycling) to accommodate wind is emissions-intensive, implying that marginal emission rates are the appropriate measure of emissions savings. Their operations research simulation model suggests that emissions savings may be completely eroded in some scenarios due to cycling-related emissions. A recent study by Bentek Energy LLC (2010) raises similar concerns about emissions associated with cycling. Engineering simulations of gas turbines in Katzenstein and Apt (2009) find that while 80% of hypothetical CO_2 savings can be achieved, only 30-50% of expected NO_x savings will be realized due to cycling.

These concerns have even led some to claim that wind power produces no emissions savings. For example, Michael J. Trebilcock states: "There is no evidence that industrial wind power is likely to have a significant impact on carbon emissions." (Trebilcock 2009). Given the widely varying assumptions and findings in the papers above, there is clearly a need for a careful analysis of actual changes in emissions associated with wind generation. Such an analysis must capture both the marginal unit of generation displaced by wind as well as the marginal emissions from that displaced generation. This study helps to fill this crucial gap in the literature, and provides emission savings estimates based on large sample empirical data that will be of use to policymakers and future researchers.

Our study is in line with two recent economics papers (Callaway and Fowlie 2009; Novan 2011) that stress the fact that emissions savings are unlikely to be constant over space, time, or even at a single plant, and therefore methods that rely on assuming average or constant emissions savings are likely to be incorrect.[6] Callaway and Fowlie (2009) use observed CO_2

[6] Both Callaway and Fowlie (2009) and Novan (2011) provide useful reviews of the existing emission savings estimation strategies and their limitations. Briefly, these can be grouped into average emission methods, dispatch model methods, and load following methods.

emissions and generation to identify the marginal operation emissions rate (MOER) in New England and New York from 2004-2007. This MOER represents the predicted amount of CO_2 that would be offset by a MWh of wind power; they find substantial variation in the MOER over the course of the day.[7] Building on Callaway and Fowlie (2009), Novan (2011) develops a theoretical model demonstrating that subsidies correlated with emissions savings will induce more efficient siting decisions by wind farm developers than the current policy of production subsidies. As this result is driven by the fact that emissions savings per unit of production are not constant, he estimates emissions savings in ERCOT to highlight the variability in emission savings rates even within a single territory. In particular, he shows that emissions savings per unit of wind power vary considerably with the load level, due to the fact that at low levels of load, coal is the marginal fuel, while at high levels of load, gas is the marginal fuel.

Building on the insights from Cullen (2011), Callaway and Fowlie (2009) and Novan (2011), we estimate the emissions savings from wind generation across several Independent System Operator (ISO) territories in the United States. We exploit exogenous variation in hourly wind generation levels to identify the effect of wind generation on total hourly emissions of SO_2, NO_x, and CO_2. Thus, our reduced-form estimation implicitly captures both the marginal unit of generation displaced by wind, as well as the marginal emissions

[7] It should be noted that Callaway and Fowlie (2009) do not have actual wind generation data for New York and New England. Mesoscale climate modeling is used to produce wind speed profiles which are then used to predict wind generation. This spatial and temporal wind generation in turn is mapped against the estimated MOER to predict emission reductions. A key assumption of this approach is that a change in wind power is equivalent to an equal and opposite change in demand, which is likely to be true when variation in wind generation is roughly in line with variation in demand. This assumption may be strained as wind capacities increase and the potential for increasingly large variation in wind generation increases the aggressiveness of cycling to accommodate intermittency.

reduction from that unit. In total, our rich data set contains over 50,000 hourly measurements of wind generation and emissions across Texas, California, and the Upper Midwest. We focus on ERCOT 2007-2009 (Texas), CAISO 2009 (California), and MISO 2008-2009 (Upper Midwest) for two reasons: first, they contain a significant portion (roughly 60%) of total wind capacity and generation in the United States, and second, these territories vary substantially in terms of their existing fossil fuel generation mix. MISO's generation is dominated by coal, CAISO's generation is dominated by gas, and ERCOT's generation is roughly an even mix of both. This variation in existing generation will prove crucial in determining the emissions savings from wind generation in each territory.

We find that emissions savings across territories are less than the hypothetical savings based on average emission rate analysis. Nonetheless we do find that emissions savings from wind generation are statistically different than zero for most pollutants and vary substantially across territories. In coal dominated MISO, we find emissions savings of 4.1 lbs/MWh for SO_2, 1.7 lbs/MWh for NO_x, and 0.92 tons/MWh for CO_2. By contrast in CAISO, where wind typically offsets gas generation, we find emissions savings of 0.01 lbs/MWh for SO_2, 0.05 lbs/MWh for NO_x, and 0.29 tons/MWh for CO_2. Generation in ERCOT is roughly evenly balanced between coal and gas, and we find that emission savings in ERCOT fall in between MISO and CAISO, with emissions savings of 1.3 lbs/MWh for SO_2, 0.79 lbs/MWh for NO_x, and 0.52 tons/MWh for CO_2. These results suggest that emissions savings are strongly driven by differences in existing generation mix - coal-intensive territories experience larger reductions in emissions due to wind generation.

Consistent with Novan (2011), hour-by-hour estimates of emissions savings also vary substantially by time of day, as the generation mix and operation within a territory change over the course of a day. This further confirms the importance of considering the marginal unit of generation displaced by wind and highlights the fact that average emission rates are an inappropriate measure of emission savings. Finally, we note that while the emission savings benefits of wind power are roughly equal to the PTC subsidy in MISO, benefits fail to cover the subsidy in ERCOT and CAISO.

2 Accommodating wind on the electricity grid

In contrast to other goods, electricity requires instantaneous matching of supply and demand. As a general rule, lower marginal cost sources of generation (coal and nuclear) are utilized by the grid first, followed by higher marginal cost sources (typically gas) as the load increases.[8] While requiring substantial initial capital investment, wind is a near-zero marginal cost source of generation, and electricity generated by wind power is almost always taken by the grid when available. As a result, intermittent production of wind power requires rapid adjustment of fossil generation in response to increases or decreases in wind generation. Figure 1 displays the ERCOT generation mix from November 5th through November 12th in 2008. This figure reveals substantial variation in wind power produced at any given point in time. During high load periods (middle of the day), substantial gas generation is online, and variation in wind power is accommodated by gas cycling. By contrast, during low load periods (overnight), limited gas generation is available, and variation in wind power is accommodated by coal cycling (as evidenced by the drop in coal generation relative to the

[8] It should be noted that coal and nuclear generation are designed to operate at a relatively constant level of output to meet baseload demand. Peak demand is frequently met by gas generators which are designed to operate at more variable levels of output and can be cycled quickly.

base level output during periods of large overnight wind generation).

A key contribution of Cullen (2011) (and echoed in Callaway and Fowlie (2009) and Novan (2011)) is recognizing that the unit of generation used to accommodate wind is not a proportional unit of the generation mix, which, given the heterogeneity in emissions by generation source, will have important implications for emissions savings. So while gas and coal represent 43% and 37% of actual generation in ERCOT, Cullen (2011) finds that wind power is accommodated primarily by gas, 72%, with the remainder, 28%, accommodated by coal. In other words, for every MWh of wind power that is supplied to the grid, on average 0.72 MWh of gas and 0.28 MWh of coal is taken off the grid. Accounting for this marginal unit of accommodation is crucial, as the environmental profile of average coal and gas generation are very different, with coal producing ten times as much NO_x, over twice as much CO_2, and vastly more SO_2. In sum, the marginal unit of accommodation does not equal the average unit of generation - a crucial feature that any estimation strategy of emissions must account for.

It is also important to account for the marginal emissions associated with the unit of generation displaced by wind power. As noted in Liik et al. (2003), the ramping up and down of gas and coal generation in response to stochastic variation in wind generation effectively increases the emissions per MWh from coal and gas. Just as automobiles are most fuel-efficient (and thus have the least emissions-per-mile) when driven steadily at approximately 55 mph, coal-fired and gas-fired plants will have lower emission rates when operated steadily at their designed level of output. Thus, as seen in figure 1, when coal plants are cycled down to accommodate wind, those plants will be operating at an inefficient level of output, raising emissions rates. Therefore, while Cullen (2011) captures the marginal unit of generation used to accommodate wind, the reliance on average emission rates from that accommodating unit may overestimate the emissions savings from wind generation. By contrast, our study (as well as Callaway and Fowlie (2009) and Novan (2011)) captures the feature that marginal emissions saved per MWh of wind generation is unlikely to be equal to the average emissions for the accommodating unit of generation.

3 Data

Our dataset consists of over 50,000 hourly observations of total wind generation in MWh and total emissions in pounds of SO_2 and NO_x and tons of CO_2 in ERCOT (2007-2009), MISO (2008-2009), and CAISO (2009). When properly identified, changes in aggregate wind generation can be causally linked to changes in aggregate SO_2, NO_x and CO_2 emissions within each territory.

3.1 Emissions

Hourly emissions data is sourced from the Environmental Protection Agency's (EPA) Continuous Emission Monitoring Systems (CEMS) program, which requires coal and gas power units with over 25 MW of capacity to submit hourly data on SO_2, NO_x and CO_2 emissions.[9]

[9] Units subject to CEMS requirements are mandated to report continuous hourly emissions based on either direct gas measurements or continuous fuel feed monitoring and mass balance calculations. While not required to report emissions, units below 25 MW do participate in the power generation markets and therefore in balancing wind generation. In order to understand the potential impact these units have on the estimates below, the contribution of units under 25 MW during 2010 was calculated from EIA 902 and EIA 923 datasets. In MISO and ERCOT, generation from these small plants was substantially less than 1% of total fossil generation, while in CAISO, small plant generation was less than 4% of total fossil generation. To these extent that these plants are used for wind balancing, the emission estimates reported below will be very slightly underestimated.

These emission reports are required by the EPA to monitor compliance with emission regulations, and strict quality assurance standards are in place to guarantee the accuracy of emission measurements.[10] However, emissions per territory are not explicitly reported under CEMS. To determine which units operated in a given area, each unit is spatially referenced using latitude/longitude against the spatial footprint of each operating territory, obtained through the operating territory's website. Units that fall under the spatial footprint of the territory are assumed to provide generation to the corresponding territory and the emissions from that plant are included in the territory's total emissions. Thus, an observation consists of the total hourly emissions of each pollutant by territory, representing the sum of emissions from all units.[11]

3.2 Wind generation

The hourly wind generation data is acquired from each operating territory (ERCOT, MISO, CAISO) and represents total electricity generation from wind turbines operating in the territory. This publicly available data, directly reported by the operating territory, is posted on the operators' websites.[12] It should be noted that the availability of hourly wind

[10] For example, under the Acid Rain Program, reported SO_2 emissions by plant are checked against allowance holdings. See http://www.epa.gov/airmarkt/emissions/continuous-factsheet.html for further details on CEMS. While CO_2 is currently an unregulated pollutant, units are still required to submit hourly CO_2 emission data.

[11] It is important to note that, while we do not directly observe the balancing response of system operators and fossil plants to changes in wind generation, the emissions consequences of these actions in response to wind generation (ramping of generation, start-up and shut-down of fossil plants, maintaining spinning reserves) are observed through the reported level of emissions.

[12] ERCOT wind generation data is available at http://planning.ercot.com/data/hourly-windoutput/, MISO wind generation data is available at https://www.midwestiso.org/Library/MarketReports/Pages/MarketReports.aspx, and CAISO wind generation data is available at http://www.caiso.com/1817/181783ae9a90.html.

generation data is the primary limiting factor of our analysis, both in terms of the time period and territories over which data is available. Wind generation data is available for ERCOT from 2007, for MISO from 2008, and for CAISO from 2009. We collected this data for each of these three territories through December 31st, 2009.[13] The 50,000 hourly observations of wind generation in our dataset thus provide a detailed look at actual wind generation levels across the three territories. Furthermore, the three territories we study account for over 60% of total wind capacity and generation in the United States.

3.3 Load and Temperature

Given a level of capacity, demand for electricity (load) is the key driver of emissions. Hourly load from each operating territory was obtained from each operator's website. While the effect of temperature on electricity demand and thus emissions (Valor et al. 2001) will be captured via hourly load, in order to account for any additional variation in emissions due to temperature (for example, through plant operating efficiency), hourly temperature is also included in our analysis. Temperature data for all territories is taken from the National Oceanic and Atmospheric Administration's (NOAA) hourly temperature database, which is available through subscription to NOAA's hourly surface data. A population-weighted average is created for each operating territory utilizing the major population centers

[13] In addition, hourly wind generation data was obtained from the Bonneville Power Authority (http://www.bpa.gov/corporate/WindPower) for 2008-2009, and from the Public Service Company of Colorado (PSCO) for January 2009. However, given the substantial hydropower resources and the fact that BPA frequently exports wind generation to neighboring territories, estimating emissions reductions is significantly complicated. PSCO does not publicly provide wind generation reports, and the January 2009 values were captured from a graph via image processing. Despite the limitations of these two datasets, analysis was performed on these territories as robustness checks of our results for MISO, ERCOT and CAISO.

within the territory's footprint. These average hourly temperatures are used throughout the analysis.

3.4 Summary statistics

Table 1 reports summary statistics regarding hourly emissions, wind generation and temperature for ERCOT, MISO and CAISO over the years of available data for each territory. During the 2007-2009 period, average yearly total generation in ERCOT was 306.3 million MWh, with wind power representing 4.7% of total generation. Coal accounted for 37% of total generation and gas accounted for 43% of generation. ERCOT average emission rates across all forms of generation was 2.63 lbs/MWh for SO_2, 0.72 lbs/MWh for NO_x, and 0.64 tons/MWh for CO_2. ERCOT average emission rates from fossil generation only was 3.29 lbs/MWh for SO_2, 0.90 lbs/MWh for NO_x, and 0.80 tons/MWh for CO_2.

During the 2008-2009 period, average annual total generation in MISO was 566.2 million MWh, with wind power representing 2% of total generation. MISO relies primarily on coal generation with 80% of total generation coming from coal and only 2.7% from gas. In coal-dominated MISO, average emission rates are substantially higher than in ERCOT, at 5.74 lbs/MWh for SO_2, 2.15 lbs/MWh for NO_x, and 0.86 tons/MWh for CO_2. Average emissions rates from fossil generation in MISO were 6.94 lbs/MWh for SO_2, 2.60 lbs/MWh for NO_x, and 1.04 tons/MWh for CO_2.

In 2009, total generation in CAISO was 178.6 million MWh, with wind power accounting for 3.2% of total generation.[14] CAISO has no coal plants in their territory, while 35% of total

[14] It should be noted that this measure of total generation, as reported by CAISO, also includes net imports, which constitute over a quarter of the reported total generation. The total generation reported above for ERCOT and MISO also include net imports, though

generation (including net imports) came from gas. Due to the lack of coal plants, average emission rates in CAISO were much cleaner than ERCOT or MISO, at 0.00 lbs/MWh for SO_2, 0.37 lbs/MWh for NO_x, and 0.16 tons/MWh for CO_2. Average emission rates from fossil generation in CAISO were 0.00 lbs/MWh for SO_2, 1.06 lbs/MWh for NO_x, and 0.46 tons/MWh for CO_2. The heterogeneity in emission rates and generation sources across these three territories will prove important in understanding the emission savings from wind emissions.

4 Empirical strategy

Our identification strategy hinges on exploiting the exogenous and stochastic variation in hourly wind power generation. The reduced-form model presented below captures the systematic response of conventional generation (and thus emissions) to hourly fluctuations in wind generation. Total emissions E_{irt} of pollutant i in territory r at hour t are separately regressed by territory against total hourly wind generation in each territory W_{rt} (in MWh), hourly load L_{rt}, average hourly temperature T_{rt} and its square T_{rt}^2 in each territory, and a vector of other control variables X_t:

$$E_{irt} = \alpha_{ir} + \beta_{ir} W_{rt} + \gamma_{1ir} L_{rt} + \gamma_{2ir} T_{rt} + \gamma_{3ir} T_{rt}^2 + \delta_{ir} X_t + \epsilon_{irt}. \tag{1}$$

The coefficient of interest is β_{ir}, which represents the marginal change in emissions in each territory due to a change in wind generation.[15] Thus, for every MWh of wind generation

they are much smaller as a percentage than CAISO (1% and 5% respectively).

[15] This coefficient represents the average marginal effect of wind power in the territory during the time period when data was available (ERCOT 2007-2009, MISO 2008-2009, CAISO 2009). While the estimated coefficients provide a clear view of the emission savings by terri-

produced in hour t in territory r, this coefficient represents the reduction in lbs/lbs/tons of $SO_2/NO_x/CO_2$. Standard errors for all estimations reported below correct for heteroscedasticity and autocorrelation.[16]

The remaining covariates control for trends in wind generation and emissions that may be correlated, leading to erroneous interpretations of β_{ir}. As load is the primary driver of emissions, load is included as a covariate. While the effect of weather on emissions is primarily captured through the load variable, temperature and its square are also included.[17] The remaining covariates in the vector X_t are fixed effects to account for other sources of variation in emissions. Hourly fixed effects are included to account for diurnal wind variation over the course of the day, which can be correlated with changes in the electricity demand profile. On average, winds are strongest in the early morning hours when electricity demand and emissions are at their nadir, and therefore failing to control for this hourly variation would lead to an overestimate of the emissions reductions from wind.

tory in the specified time periods, it is important to note that these coefficient estimates are subject to the generation mix, wind capacity, and other relevant factors as they existed during those years. As such, structural estimation or simulated dispatch models may be more appropriate for estimating future emissions savings from wind. Nonetheless, the reduced-form estimates reported below provide insight into actual emission savings and can serve as a useful baseline for follow-up studies.

[16] Standard tests (Augmented Dickey-Fuller, Phillips-Perron) reject the presence of a unit-root. Newey-West standard errors are reported with lags for each pollutant and territory selected by examination of the autocorrelation function. Standard errors estimated with the Newey-West automatic lag selection from Newey and West (1994) yielded identical results. Estimates with weekly clustered standard errors are also conducted and are reported as a robustness check below. While a seemingly unrelated regressions (SUR) model would appear to be appealing, the fact that the right-hand side regressors are identical within each territory implies that the SUR estimates will be identical to the OLS estimates reported below. Also, given the geographic distance between territories, error terms are uncorrelated across territories.

[17] Estimations were run with heating-degree day and cooling-degree day specifications instead of temperature, generating coefficients and standard errors that differed only trivially from those reported.

Over the sample period, wind capacity steadily increased, which may be correlated with changes in demand and emissions driven by macroeconomic effects unrelated to wind generation. To account for these longer-run trends, month-year fixed effects are also included in X_t, leading to identification of the effect of wind generation on emissions through within-month variation.[18] Finally, though wind generation is not correlated with the day of the week, day-of-week fixed effects are included in X_t to capture within-week variation (primarily between weekdays and weekends) in electricity demand and emissions. In addition to the central results presented below, we report a number of robustness checks on our specification including estimates with load-hour fixed effects, estimates with month-hour fixed effects, estimates without load, and estimates with daily aggregates.

5 Results

5.1 Hourly estimates

The estimates of the emission savings from wind generation in ERCOT, MISO, and CAISO from our base specification are presented in table 2. The reported coefficients in the first row can be interpreted as the lbs/lbs/tons of $SO_2/NO_x/CO_2$ emissions reduced per MWh of wind generation. The first three columns represent the emissions savings by pollutant due to wind power in ERCOT from 2007-2009. Each MWh of wind generation in ERCOT on average reduced SO_2 by 1.277 lbs, NO_x by 0.710 lbs, and CO_2 by 0.523 tons. All coefficients are very statistically significant. The next three columns represent emission savings in coal

[18] Alternative specifications with month and year fixed effects or flexible polynomial time trends yielded estimates nearly identical to those presented below.

dominated MISO from 2008-2009, where each MWh of wind generation in MISO reduced SO_2 by 4.106 lbs, NO_x by 1.735 lbs, and CO_2 by 0.916 tons. Again, all coefficients are statistically significant and are larger than the estimated emissions savings in ERCOT. By contrast, in gas dominated CAISO, we find emissions savings in 2009 of 0.008 lbs/MWh for SO_2, 0.051 lbs/MWh for NO_x, and 0.286 tons/MWh for CO_2, with significant coefficient estimates for NO_x and CO_2. Coefficients for the effect of temperature on emissions are also reported. Coefficients for the linear and quadratic temperature terms are significant across pollutants and territories, and as expected, reflect a U-shaped relationship between temperature and emissions with minimums occurring around an average of 56 °F.

The estimated emission savings in ERCOT using average plant emission rates found in Cullen (2011) provide a useful reference point. Cullen calculates that 3.15 lbs of SO_2, 1.05 lbs of NO_x, and 0.71 tons of CO_2 were avoided per MWh of wind power in ERCOT from 2005-2007. By contrast, our estimates for ERCOT (2007-2009) above find substantially smaller emission savings rates of 1.277 lbs/MWh for SO_2, 0.710 lbs/MWh for NO_x, and 0.523 tons/MWh for CO_2. This difference is likely driven by emissions associated with cycling - as noted in Katzenstein and Apt (2009), only 30-50% of expected NO_x savings will be realized due to emission increases from cycling gas turbines. It should be noted that this comparison may actually understate the reduction in emission savings caused by cycling, as it compares emission savings rates from Cullen's 2005-2007 estimates against our 2007-2009 estimates. Re-estimating our model with 2007 data only, we find smaller SO_2 reductions of 0.88 lbs/MWh, NO_x reductions of 0.41 lbs/MWh, and CO_2 reductions of 0.38 lbs/MWh. Increased emission savings rates in ERCOT in 2009 likely stem from increases in wind capacity and generation that required increased accommodation by coal generation.[19]

Before concluding the discussion of our base specification hourly estimates of emissions savings, one concern worth discussing is the import and export response to wind generation in a territory. The particular concern is that, if import and export decisions are adjusted in response to changes in wind generation (for example, reducing imports or increasing exports of generation when wind levels are high), estimated emissions savings will be underestimated (biased towards zero) as the changes in emissions will occur at thermal plants outside the territory's operating footprint. How concerned should we be about this potential downward source of bias?

ERCOT is relatively isolated from the rest of the national electrical grid, and as such we might expect limited import or export response to changes in wind generation. Cullen (2011) notes that less than 1% of ERCOT's total generation is exchanged across its limited ties. However, despite the small absolute amount of transmission, what we should be concerned about is changes in imports and exports in response to changes in wind. We obtained hourly import and export data for ERCOT from 2007-2009 and estimated net imports against wind generation (utilizing the same controls as the emission estimation in equation 1). Estimated changes in net imports due to wind generation were small (-0.06 MWh of net imports per 1 MWh of wind) but statistically significant (p-value < 0.01). This implies that roughly 0.06 MWh per 1 MWh of wind is exported out of ERCOT, suggesting our estimates of emissions savings above are slightly downward biased.

[19] In addition to hourly emissions data for ERCOT, we also obtained hourly coal MWh generation for 2007-2009. Estimates of the displacement of coal by wind power in 2007 versus 2009 suggest that more coal was displaced as wind capacity grew, which concurs with findings in Bentek Energy LLC (2010) that the number of wind-induced coal cycling events in ERCOT doubled from 2007 to 2009.

In contrast to ERCOT's isolation, CAISO is substantially connected to neighboring territories and is very import dependent, with roughly a quarter of their load met by imports. Perhaps the small emissions savings in CAISO could be explained by the fact that CAISO adjusts its hourly import levels in response to wind power generated. To test this hypothesis, we obtained hourly net import levels in the CAISO territory and estimated net imports against wind generation. Estimated changes in net imports due to wind generation were small (-0.05 MWh of net imports per MWh of wind) and statistically insignificant (p-value = 0.50), suggesting that CAISO is not adjusting import levels in response to wind generation.[20]

Finally, MISO is less import-dependent than CAISO but more-so than ERCOT. We obtained hourly import and export data (including the name of the exporting or importing territory) for MISO to test for any import or export response to wind generation levels. We find some evidence of a response of net imports to wind generation, with a reduction of 0.15 MWh of net imports per MWh of wind generation (p-value = 0.01). While the bulk (80%) of the import response is from hydro and nuclear-dominated territories (Manitoba Hydro Electric Board (MHEB), Ontario's Independent Electricity System Operator (IESO), eastern interconnection region (WAUE) of the Western Area Power Administration (WAPA)), to the extent that reductions in exports to MISO from these areas implies that thermal generation may be offset elsewhere, the emission saving estimates for MISO may be slightly underestimated.

[20] This is consistent with CAISO documents which state that import scheduling occurs ahead of time and in blocks of one hour. Such a system may be too inflexible to adjust in response to wind intermittency.

5.2 Robustness checks

The previous section used hourly exogenous variation in wind generation to estimate the emission savings rate per MWh of wind generation in ERCOT, MISO and CAISO. We now examine the robustness of our estimates to a number of alternative specifications. Emission savings estimates under several alternative specifications are reported in table 3 and in general are consistent with the base specification results in table 2.[21] Emissions savings for ERCOT are in the range of 1.246-1.386/0.665-0.790/0.489-0.523 lbs/lbs/tons of $SO_2/NO_x/CO_2$ per MWh of wind generation. Emissions savings for MISO are larger than ERCOT for all specifications and are in the range of 3.295-4.890/1.438-1.995/0.850-1.025 lbs/lbs/tons of $SO_2/NO_x/CO_2$ per MWh of wind generation. Emissions savings for CAISO are the smallest and are in the range of 0.006-0.008/0.010-0.054/0.202-0.299 lbs/lbs/tons of $SO_2/NO_x/CO_2$ per MWh of wind generation.

The first column presents estimates with month-hour fixed effects to capture systematic differences in hourly emissions across the year. Estimates are consistent with our base specification, with slightly smaller emissions savings found for most pollutants. The second column adds load-hour fixed effects, which allows the effect of load on emissions to vary by time of day. For example in ERCOT, this specification would capture the fact that coal is typically the marginal unit during overnight hours, while gas is typically the marginal unit during peak times (per figure 1). Estimates are again consistent with our base specification, and again slightly smaller emissions savings are found for most pollutants. Next, the third column removes load from the specification and solely relies on fixed effects and temperature to control for emission levels. The estimates under this specification are similar to those in

[21] Unless noted, Newey-West standard errors are reported for all estimates.

the base specification, with slightly smaller emission savings in ERCOT, and slightly larger emission savings in MISO and CAISO.

The fourth column reports estimates from daily aggregated values. The purpose of this specification is to address concerns that there may be dynamic effects of wind generation, such that wind power generated at time t affects emission at some later $t + n$ time period.[22] Estimates under daily aggregation are again generally consistent, albeit slightly smaller than our base specification.[23] Finally, the fifth column reports emission savings estimates with standard errors clustered at the weekly level to allow arbitrary heteroscedasticity and serial correlation. Clustered standard errors are in general slightly larger than the Newey-West standard errors reported in table 2, but the statistically significant estimates in the base scenario remain statistically significant.

5.3 Emissions savings rates across territories

The importance of the generation mix can be seen by comparing estimates of emission savings across territories. Figure 2 displays emission savings per MWh against the percentage

[22] For example, a strong morning wind event displaces substantial thermal generation, which would then require emissions-intensive ramping (which may spill over into the following hours) as the wind event diminished. Alternatively, the cycling of thermal plants in response to large levels of wind generation may negatively affect emission control technologies, resulting in increased emissions after wind generation levels have diminished.

[23] While our simple exploration is not meant to substitute for a proper dynamic analysis, these results do suggest that any dynamic effects are fairly small. Nonetheless, the fact that the daily aggregations yield the smallest emission savings estimates across specifications for most pollutants suggests that a fuller dynamic analysis may be a fruitful avenue for future research. A related concern is that the volatility of wind generation could have emission consequences that spill over multiple hours. While beyond the scope of this paper, exploring the effects of wind generation volatility on emission savings may be an important line of research as the volatility of wind power will increase in the future as wind capacity increases.

share of coal generation in each territory (fit with a quadratic polynomial).[24] Each pollutant exhibits an upward trend with respect to coal share, with emissions savings from SO_2 displaying the steepest increase. The stronger dependence of SO_2 emission savings on coal share is driven by the fact that coal is the only source of SO_2, while NO_x and CO_2 are also produced by gas. Each pollutant also exhibits a convex response to coal share. Territories with low to moderate coal share typically have a substantial volume of natural gas fired generation capacity, and it is this gas capacity that is used to accommodate wind on the grid, and thereby relatively smaller emission savings are generated. As coal share increases and gas share decreases, the ability of gas to accommodate wind is also diminished, which in turn implies that base load coal is cycled more frequently to accommodate wind, increasing emission savings.

As a crude check on our findings, we also estimated BPA 2008-2009 emissions savings and PSCO December 2009 emissions savings from wind power, despite the difficulties with these datasets. Like CAISO, BPA has a very low coal share (hydropower represents two-thirds of BPA generation), and we find similarly low emissions savings of 0.059 lbs of SO_2, 0.170 lbs of NO_x, and 0.081 tons of CO_2 per MWh of wind.[25] By contrast, PSCO has coal and gas

[24] The emissions savings equations in figure 2 for each pollutant E_i as a function of coal share C are as follows: $E_{SO2} = 4.272C^2 + 1.802C + 0.034$, $E_{NOX} = 1.309C^2 + 0.732C + 0.340$, $E_{CO2} = 0.023C^2 + 0.909C + 0.184$.

[25] These numbers are the estimated changes in emissions within the BPA footprint due to wind generation, which should be interpreted with some caution. BPA exports a substantial amount of their generation, particularly during the late spring and early summer months when heavy snowpack melt-off leads to large amounts of hydropower generation and thermal plants are run at minimum levels or completely shut down. Hourly import/export data was obtained from BPA and net exports were regressed against hourly wind generation for 2008-2009 (using all controls from equation 1). We find that net exports increased by a statistically significant 0.320 MWh per MWh of wind generation. If we combine our point estimate of emissions savings with the estimate of exports, we can determine a plausible upper-bound on total possible CO_2 emission savings from wind power in BPA. Given the

shares of generation that are similar to ERCOT, and for December 2009, we find emissions savings very similar to ERCOT of 0.900 lbs of SO_2, 0.752 lbs of NO_x, and 0.398 tons of CO_2 per MWh of wind (all statistically significant despite the limited sample).

As noted above, over the course of a day, the share of each generation type (coal vs. gas) as well as the contribution of each plant to the total generation profile varies considerably. Figures 3-5 plot the emission savings by pollutant for each territory by hour, with 95% confidence intervals included for ERCOT.[26] Figures 3-5 demonstrate that the marginal emissions savings are not constant over the course of the day, which is driven by differences in the fuel mix of generation as well as differences in emission rates across plants within a fuel type. These hourly results are generally consistent with the estimations in Novan (2011) of emissions savings against load (see figure 4 in Novan (2011)). Novan finds that SO_2 emission savings rates fall as load increases, consistent with the decreased SO_2 emissions savings during mid-day in figure 3 when demand is at its highest level and variation in wind generation is accommodated primarily by gas. By contrast, NO_x and CO_2 emissions savings rates initially decline as load increases, but then rise as load increases further. Figures 4 and 5 display somewhat higher emissions savings rates for NO_x and SO_2 during overnight periods (lowest demand) and mid-day (highest demand).

region of the country, if fossil generation is offset by these exports, it will likely be natural gas with an assumed 0.5 tons/MWh of CO_2 emissions. Thus, multiplying 0.5 tons of CO_2 emissions per MWh from gas by the 0.320 MWh exports per MWh of wind, and adding that to the 0.081 tons of CO_2 emissions saved per MWh of wind in BPA's territorial footprint yields upper-bound emissions savings of 0.241 tons of CO_2 per MWh of wind power in BPA.

[26] Each point represents a separate regression. 216 by-hour regressions were run in total, with each estimation including temperature, temperature squared, load, day-of-week fixed effects, and month-year fixed effects. Due to the shorter time series for CAISO and MISO, we cannot statistically resolve the peaks and troughs (as opposed to ERCOT), and have excluded the confidence intervals from the figures.

Finally, in table 4 we report the coal share of generation and total wind generation by state.[27] While we have estimates of emission savings from roughly 60% of total wind generation in the US, table 4 provides some insight into likely emission savings outside of ERCOT, MISO and CAISO. As the above exercise demonstrates, the coal share of generation appears to be a first-order driver of emission savings. Thus, while states like New York, Oregon and Washington have large amounts of wind generation, the fact that their coal shares are similar to California suggests that emissions savings rates in those states may be small. By contrast, states with high coal shares and high wind generation such as Colorado, Kansas, New Mexico, and Wyoming will likely have larger emissions savings rates more in line with ERCOT or MISO. Finally, while West Virginia produced a modest amount of wind power, the large coal share (96%) in the state suggests that emission savings in West Virginia may be quite large in magnitude. While the potential for substantial wind power in West Virginia is somewhat limited, states such as Kansas, Nebraska, North Dakota, Iowa, Wyoming, and New Mexico rank in the top 10 for potential wind power and have coal shares of roughly 70% or more.[28]

[27] The fraction of total electricity generation produced by coal was obtained from the EIA Electric Power Annual Report (1990-2009 Net Generation by State by Type of Producer by Energy Source (EIA-906, EIA-920, and EIA-923)) at http://www.eia.gov/cneaf/electricity/epa/epa_sprdshts.html. Total wind generation was obtained from the EIA Renewable Energy Consumption and Electricity Preliminary Statistics 2009: Table 6 at http://www.eia.doe.gov/cneaf/alternate/page/renew_energy_consump/rea_prereport.html.

[28] From the National Renewable Energy Lab's estimates of resource potential in the US at http://www.windpoweringamerica.gov/wind_maps.asp

5.4 Benefits of avoided emissions from wind power

A key issue of policy interest is the benefits of avoided emissions due to wind power. If unpriced emissions were the only market failure associated with conventional power generation, basic externality theory suggests that the optimal subsidy per MWh of wind power would be equal to the marginal social benefit of avoided emissions per MWh.[29] Such a subsidy would provide incentive for wind developers to internalize the social benefits of clean energy, leading to an efficient level of wind power production. Currently however, the federal Production Tax Credit subsidy is set at $22 per MWh of wind power, regardless of the actual emissions savings from a given MWh of wind power. How does this existing subsidy compare to the hypothetical optimal subsidy?

While we have estimated the emissions savings per MWh in Texas, California, and the Upper Midwest, valuation of those avoided emissions is a difficult task. For unregulated pollutants such as CO_2, the social damages would represent the value of avoided emissions. However, for regulated pollutants such as SO_2 and NO_x, the social costs are internalized by firms, and reductions in these pollutants will not constitute a welfare gain (assuming the regulations are appropriately set).[30] As such, figure 6 plots the emissions saving benefits per

[29] In reality, there are likely many additional market failures and externalities (both positive and negative) associated with wind power. These market failures could include reliability and integration costs of wind power (for example, the 0.6 cents per MWh integration charge levied in BPA), upstream externalities associated with coal and natural gas extraction, reductions in particulates and mercury, learning-by-doing and research and development spillovers, and noise and visual disamenities associated with turbines. However, as much of the current focus on alternative energy development revolves around emissions savings (primarily CO_2), the discussion below will focus on the marginal social benefits of wind power associated with emissions reductions.

[30] Alternatively, Cullen (2011) assumes that the marginal social damage of the regulated pollutants (SO_2 and NO_x) is equal to the market permit price, while acknowledging that such an assumption is subject to criticism. Assuming $433 dollars per ton permit prices for SO_2 and $5,000 dollars per ton permit prices for NO_x, SO_2 and NO_x reductions in ERCOT

MWh for CO_2 in each territory as the marginal social damage of CO_2 varies. The horizontal dashed line represents the \$22/MWh PTC.

One interpretation of figure 6 is that the intersection of the PTC line and the marginal benefit curve for each territory represents the marginal social damage per ton of CO_2 required for the emissions savings benefits to equal the current PTC. In coal-heavy MISO, emissions savings benefits will equal the federal production subsidy at \$24 dollars per ton of CO_2 (or at \$19 dollars per ton including SO_2 and NO_x benefits). By contrast, in ERCOT and CAISO, substantially larger values of the marginal social damage of CO_2 would be required to equal the production subsidy - roughly \$42 dollars per ton in ERCOT (\$38 per ton if regulated pollutant reductions provide social benefits), and nearly \$80 dollars a ton in CAISO. For comparison, the US Interagency Working Group On Social Cost Of Carbon selected \$21 dollars per ton of CO_2 as their central estimate of the social cost of carbon.[31] Thus, under central estimates of the marginal social damage of CO_2, emission savings benefits in ERCOT are roughly equal to the PTC, while emissions savings benefits in ERCOT and CAISO are below the production subsidy. These results also suggest that a subsidy linked to emissions savings (or a proxy such as coal share) could have generated greater emissions reductions for the same total subsidy expenditure, relative to the production-based subsidy currently in place (Novan 2011). Finally, it should be noted that even if the marginal benefits of avoided

generate benefits of \$0.28 and \$1.98 per MWh of wind, SO_2 and NO_x reductions in MISO generate benefits of \$0.89 and \$4.34 per MWh of wind, and SO_2 and NO_x reductions in CAISO generate benefits of \$0.00 and \$0.13 per MWh of wind.

[31] See "Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866" at http://www.epa.gov/oms/climate/regulations/scc-tsd.pdf and Greenstone et al. (2011) for further details on methodologies and assumptions. The central estimate assumed a 3% discount rate - at a 5% discount rate, the social cost of carbon was \$5 dollars per ton of CO_2.

emissions exceeded the production subsidy, that does not imply that wind power production subsidies are the most cost-effective instrument for emissions reductions.[32]

6 Conclusions

In the preceding sections, we provided estimates of emissions savings from wind power in Texas, California and the Upper Midwest. Our reduced form approach leverages the exogenous variation in hourly wind production to identify the impact of wind power on system-wide emissions. Looking to the future, accommodation of wind onto the grid will become an increasingly important issue, as wind was the second largest new source of installed capacity in the US in 2008 and 2009. This paper has provided strong evidence that the emissions savings corresponding to this growth in wind power will vary substantially depending on the fuel source displaced by wind. In particular, the share of coal in the existing generation mix strongly influences emissions savings from wind. This suggests that there may be benefits to adjusting the existing Production Tax Credits to reflect the regional emission savings (or a proxy thereof) from a MWh of wind power.

Based on current trends, several competing forces will influence emissions savings from wind power in the future. First, gas is the leading source of new generation capacity in the US, due to decreasing fuel costs relative to coal as well as concern about stronger EPA regulation of coal plants. This would tend to increase the gas offset by wind power and reduce

[32] Fischer and Newell (2008) develop a calibrated numerical analysis to rank alternative mechanisms for climate mitigation, and renewable production subsidies rank fifth in terms of cost-effectiveness out of the six policies considered. Not surprisingly, a direct emissions pricing mechanism such as a tax or tradable permit emerged as the most cost-effective instrument.

the emission savings associated with wind (although of course electricity generation from gas itself is less emissions-intensive than coal). Second, as wind capacity grows, the ability of existing gas generation to accommodate wind power will diminish, leading to increased cycling of coal plants (as seen in ERCOT), potentially increasing emissions savings. Finally, increasing wind penetration will likely require an increase in ramping of thermal generation, as the magnitude of shifts in wind speed is amplified into larger swings in aggregate wind generation. This increased cycling of thermal generation (in magnitude and potentially frequency) may erode the emissions savings per MWh of wind power as thermal generation is utilized less efficiently to accommodate wind. While it is unclear which of these effects will win out, it is clear that the resulting emission savings of wind power will depend critically on the factors highlighted in this paper. As such, this paper provides a transparent framework for updating and refining emission savings estimates as data on wind generation in more territories and across longer time periods becomes available.

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Table 1: Hourly wind power generation and emissions by territory

		Mean	Standard Deviation	Maximum	Minimum
ERCOT	Sulphur dioxide	91.9	13.1	141	42.5
	Nitrogen oxides	25.2	6.13	62.5	10.8
	Carbon dioxide	22.3	4.63	38.9	11.0
	Wind generation	1.63	1.20	6.04	0
	Temperature	67.4	17.3	107	18
MISO	Sulphur dioxide	371	69.6	580	198
	Nitrogen oxides	139	43.7	260	63.8
	Carbon dioxide	56.6	8.50	83.9	32.8
	Wind generation	1.32	0.96	5.40	0
	Temperature	49.2	19.5	89.2	-11
CAISO	Sulphur dioxide	0.04	0.06	0.84	0.01
	Nitrogen oxides	0.76	0.40	4.84	0.17
	Carbon dioxide	3.17	1.36	9.37	0.49
	Wind generation	0.65	0.48	1.86	0
	Temperature	61.0	8.56	89.9	29.8

Notes: Variables are reported as follows: SO_2 and NO_x in thousands of pounds, CO_2 in thousands of tons, wind power in thousands of MWh, and temperature in degrees Fahrenheit. ERCOT values represent 26,280 observations from 2007-2009, MISO values represent 15,520 observations from 2008-2009, and CAISO values represent 8760 observations from 2009.

Table 2: Estimation results for emissions reductions from wind generation by territory - hourly

	ERCOT			MISO			CAISO		
Pollutant	SO_2 (lbs)	NO_x (lbs)	CO_2 (tons)	SO_2(lbs)	NO_x (lbs)	CO_2 (tons)	SO_2(lbs)	NO_x (lbs)	CO_2 (tons)
Wind (MWh)	-1.277**	-0.790**	-0.523**	-4.106**	-1.735**	-0.916**	-0.008	-0.051*	-0.286**
	(0.183)	(0.036)	(0.017)	(0.722)	(0.220)	(0.064)	(0.007)	(0.023)	(0.045)
Temp (° F)	-295.9**	-461.2**	-233.7**	-1531**	-521.0**	-230.7**	-10.53	-29.66	-5.840*
	(107.3)	(26.54)	(11.10)	(235.6)	(126.0)	(2.553)	(6.112)	(2.315)	(2.412)
Temp^2	2.262**	4.040**	2.003**	16.65**	3.586**	2.614**	0.075	0.300	5.234*
	(0.828)	(0.214)	(0.089)	(2.278)	(1.188)	(0.263)	(0.042)	(0.208)	(0.204)
Load (MWh)	0.349**	0.515**	0.380**	4.229**	1.405**	0.593**	0.004**	0.066**	0.281**
	(0.061)	(0.012)	(0.007)	(0.153)	(0.068)	(0.015)	(0.001)	(0.005)	(0.014)
Hour FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Month-Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
DOW FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	26280	26280	26280	17520	17520	17520	8760	8760	8760
R^2	0.63	0.87	0.92	0.93	0.97	0.95	0.13	0.50	0.92

*Notes: Dependent variables: SO_2 emissions (pounds), NO_x emissions (pounds), and CO_2 emissions (tons). Newey-West standard errors in parentheses (5/5/2.5 day lags for SO_2, 1/6/2.5 day lags for NO_x, and 3/5/5 day lags for CO_2 by ERCOT/MISO/CAISO territories.) ERCOT values represent hourly 26,280 observations from 2007-2009, MISO values represent 15,520 hourly observations from 2008-2009, and CAISO values represent 8760 hourly observations from 2009. * indicates 5 percent significance, ** indicates 1 percent significance.*

Table 3: Estimation results for emissions reductions from wind generation by territory - robustness checks

		Month-Hour Fixed Effects	Load-Hour Fixed Effects	No Load	Daily Aggregation	Clustered Errors
ERCOT	SO_2 (lbs)	-1.297**	-1.368**	-1.246**	-1.273**	-1.277**
		(0.183)	(0.181)	(0.184)	(0.300)	(0.196)
	NO_x (lbs)	-0.761**	-0.744**	-0.743**	-0.665**	-0.790**
		(0.041)	(0.040)	(0.044)	(0.067)	(0.048)
	CO_2 (tons)	-0.512**	-0.518**	-0.489**	-0.506**	-0.523**
		(0.016)	(0.017)	(0.030)	(0.025)	(0.017)
MISO	SO_2 (lbs)	-3.810**	-3.894**	-4.890**	-3.295**	-4.106**
		(0.722)	(0.705)	(0.922)	(0.927)	(0.725)
	NO_x (lbs)	-1.642**	-1.675**	-1.995**	-1.438**	-1.735**
		(0.216)	(0.222)	(0.281)	(0.296)	(0.220)
	CO_2 (tons)	-0.868**	-0.890**	-1.025**	-0.850**	-0.916**
		(0.059)	(0.061)	(0.103)	(0.077)	(0.060)
CAISO	SO_2 (lbs)	-0.006	-0.008	-0.008	-0.006	-0.008
		(0.006)	(0.007)	(0.007)	(0.009)	(0.007)
	NO_x (lbs)	-0.018	-0.038	-0.054*	-0.010	-0.051*
		(0.025)	(0.024)	(0.027)	(0.031)	(0.023)
	CO_2 (tons)	-0.240**	-0.275**	-0.299**	-0.202**	-0.286**
		(0.046)	(0.045)	(0.073)	(0.065)	(0.043)

*Notes: Dependent variables: SO_2 emissions (pounds), NO_x emissions (pounds), and CO_2 emissions (tons). Temperature controls include average daily temperature and average daily temperature squared. ERCOT values represent 1095 daily observations from 2007-2009, MISO values represent 730 daily observations from 2008-2009, and CAISO values represent 365 daily observations from 2009. * indicates 5 percent significance, ** indicates 1 percent significance.*

Table 4: Coal share and wind power generation 2009

	Coal share	Wind generation (MWh)		Coal share	Wind generation (MWh)
Alabama	0.39	0	Montana	0.58	810,815
Alaska	0.09	3,062	Nebraska	0.69	288,681
Arizona	0.44	9,555	Nevada	0.20	0
Arkansas	0.35	0	New Hampshire	0.14	28,466
California	0.01	5,764,637	New Jersey	0.08	19,150
Colorado	0.63	2,942,133	New Mexico	0.73	1,543,715
Connecticut	0.08	0	New York	0.10	2,258,904
Delaware	0.59	0	North Carolina	0.55	0
Florida	0.25	0	North Dakota	0.87	2,756,289
Georgia	0.54	0	Ohio	0.84	15,474
Hawaii	0.14	213,224	Oklahoma	0.45	2,271,590
Idaho	0.01	227,028	Oregon	0.06	3,372,284
Illinois	0.46	2,761,152	Pennsylvania	0.48	921,137
Indiana	0.93	1,403,192	Rhode Island	0.00	0
Iowa	0.72	7,331,391	South Carolina	0.34	0
Kansas	0.69	2,385,107	South Dakota	0.39	392,308
Kentucky	0.93	0	Tennessee	0.52	51,747
Louisiana	0.25	0	Texas	0.35	19,350,879
Maine	0.00	260,121	Utah	0.82	64,497
Maryland	0.55	0	Vermont	0.00	11,589
Massachusetts	0.27	3,798	Virginia	0.37	0
Michigan	0.66	289,188	Washington	0.07	3,538,936
Minnesota	0.56	4,956,987	West Virginia	0.96	742,439
Mississippi	0.26	0	Wisconsin	0.62	1,059,126
Missouri	0.81	498,515	Wyoming	0.91	2,213,820

Notes: Coal share represents the fraction of total state electricity generation produced from coal in 2009 (EIA). Wind generation represents total wind generation in the state for 2009 (EIA).

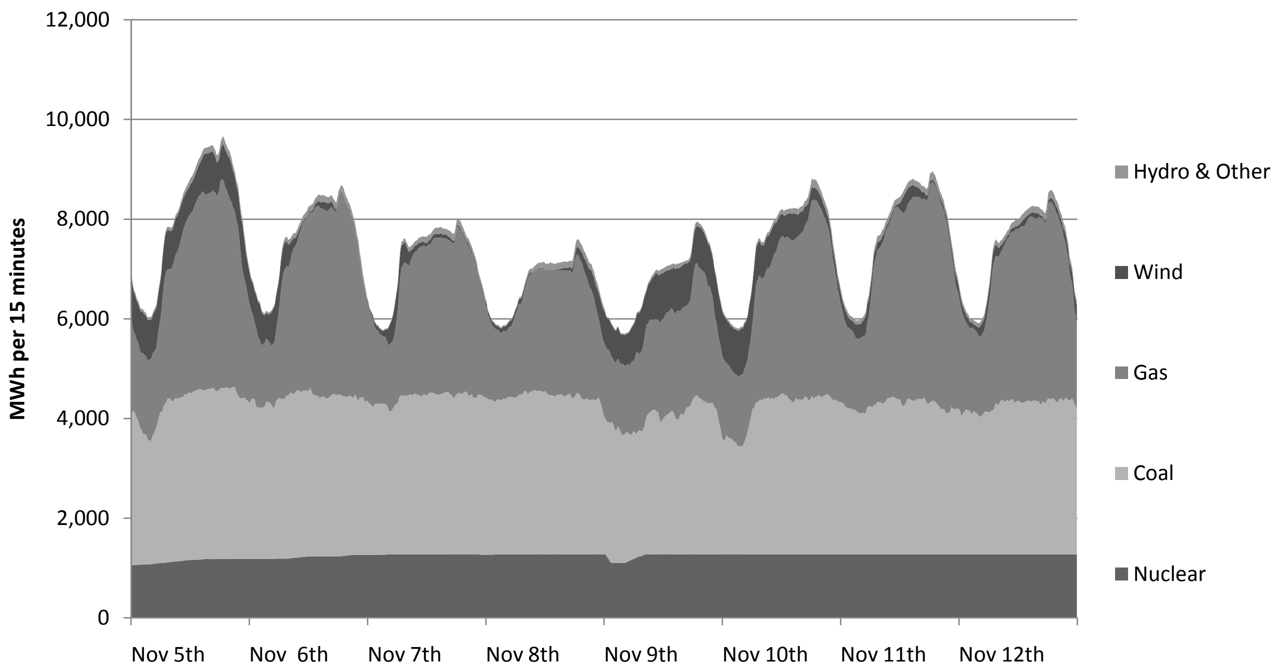

Figure 1: Generation mix in ERCOT (November 5-12, 2008)

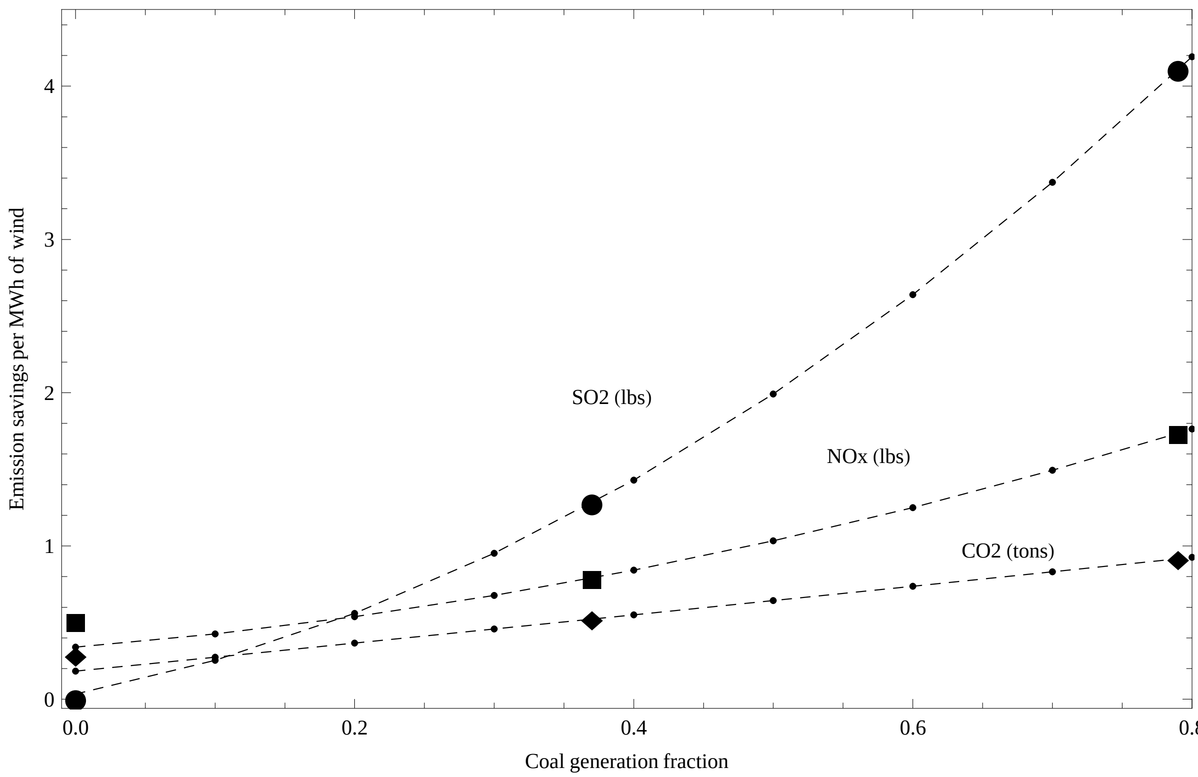

Figure 2: Emission savings per MWh of wind power against the fraction of coal generation. Plotted points indicate estimated emissions savings rates by pollutant in CAISO, ERCOT, and MISO (left-to-right). Plotted lines represent fitted quadratic polynomials for each pollutant.

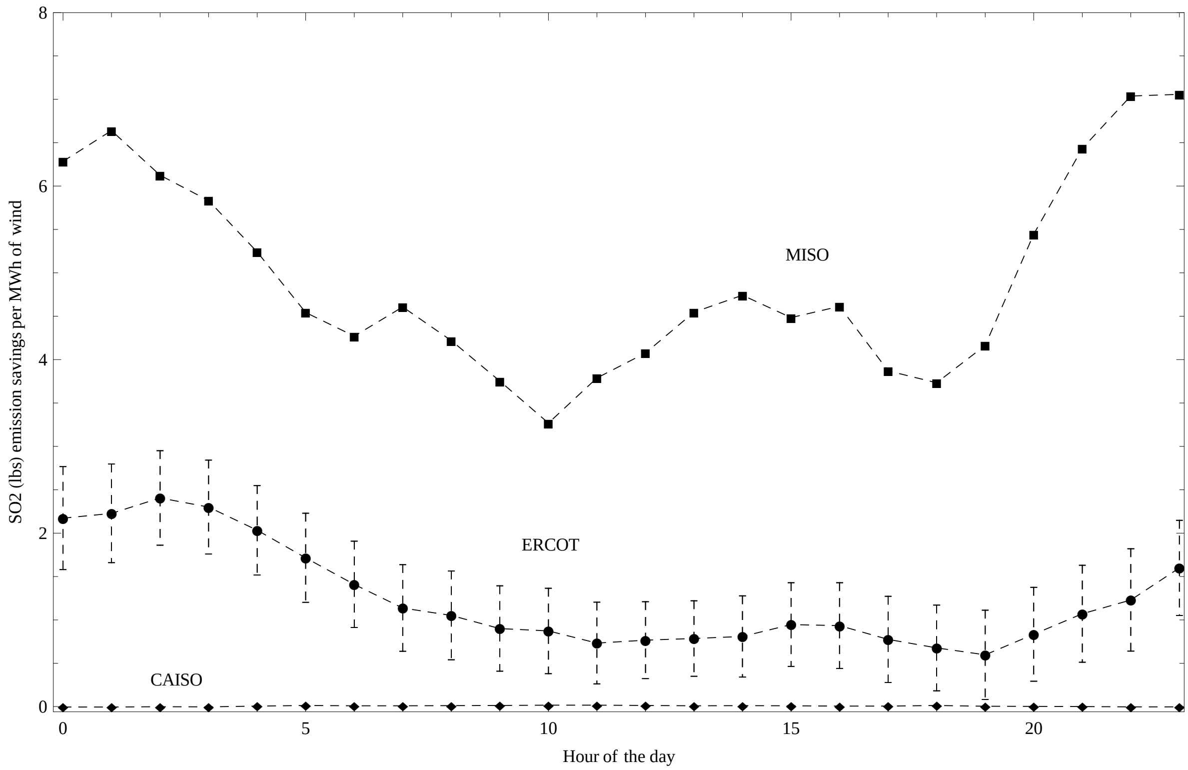

Figure 3: Hour-by-hour SO_2 emission savings per MWh of wind power by territory

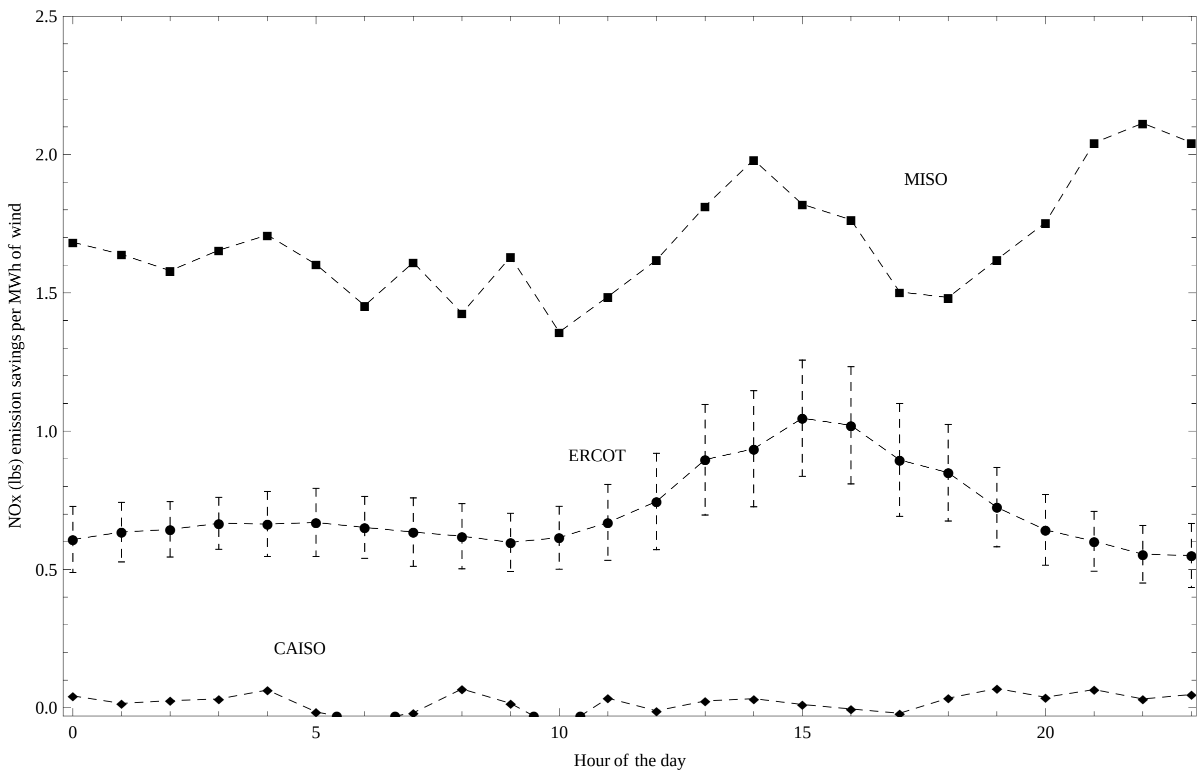

Figure 4: Hour-by-hour NO_x emission savings per MWh of wind power by territory

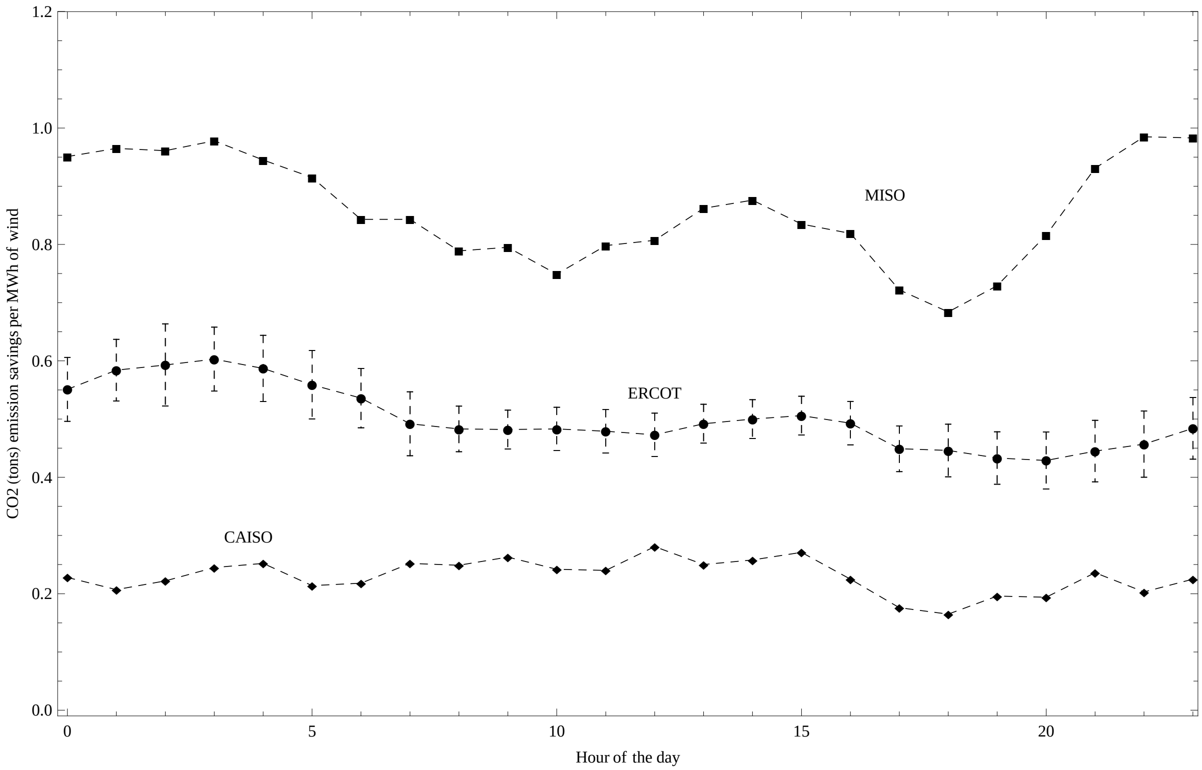

Figure 5: Hour-by-hour CO_2 emission savings per MWh of wind power by territory

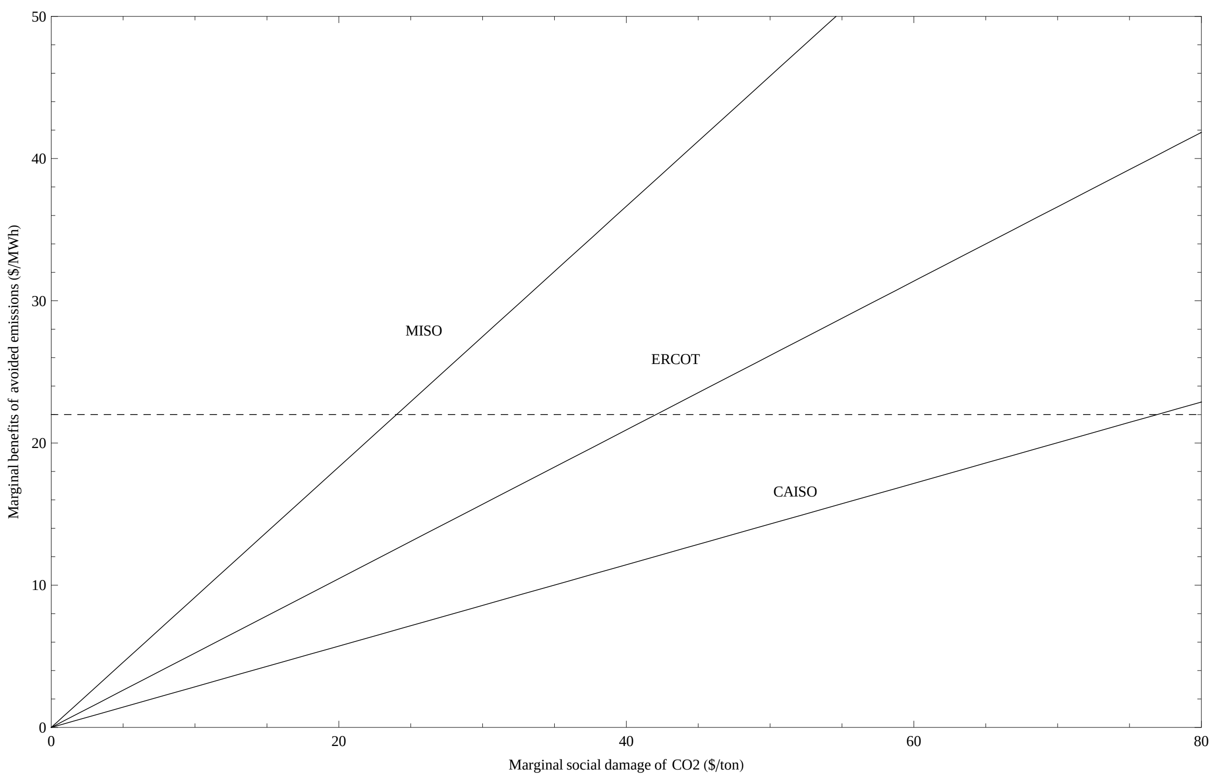

Figure 6: Marginal benefits of avoided emissions per MWh of wind power by territory for various marginal social damages of CO_2 emissions. Dashed line indicates government production subsidy for wind power.